NEW

EVERYTHING
YOU NEED TO KNOW ABOUT

MARS

THE SECRETS OF THE RED PLANET

Is life from Mars?

Can we live there?

How will we get there?

Why is Mars amazing?

Where did its sky go?

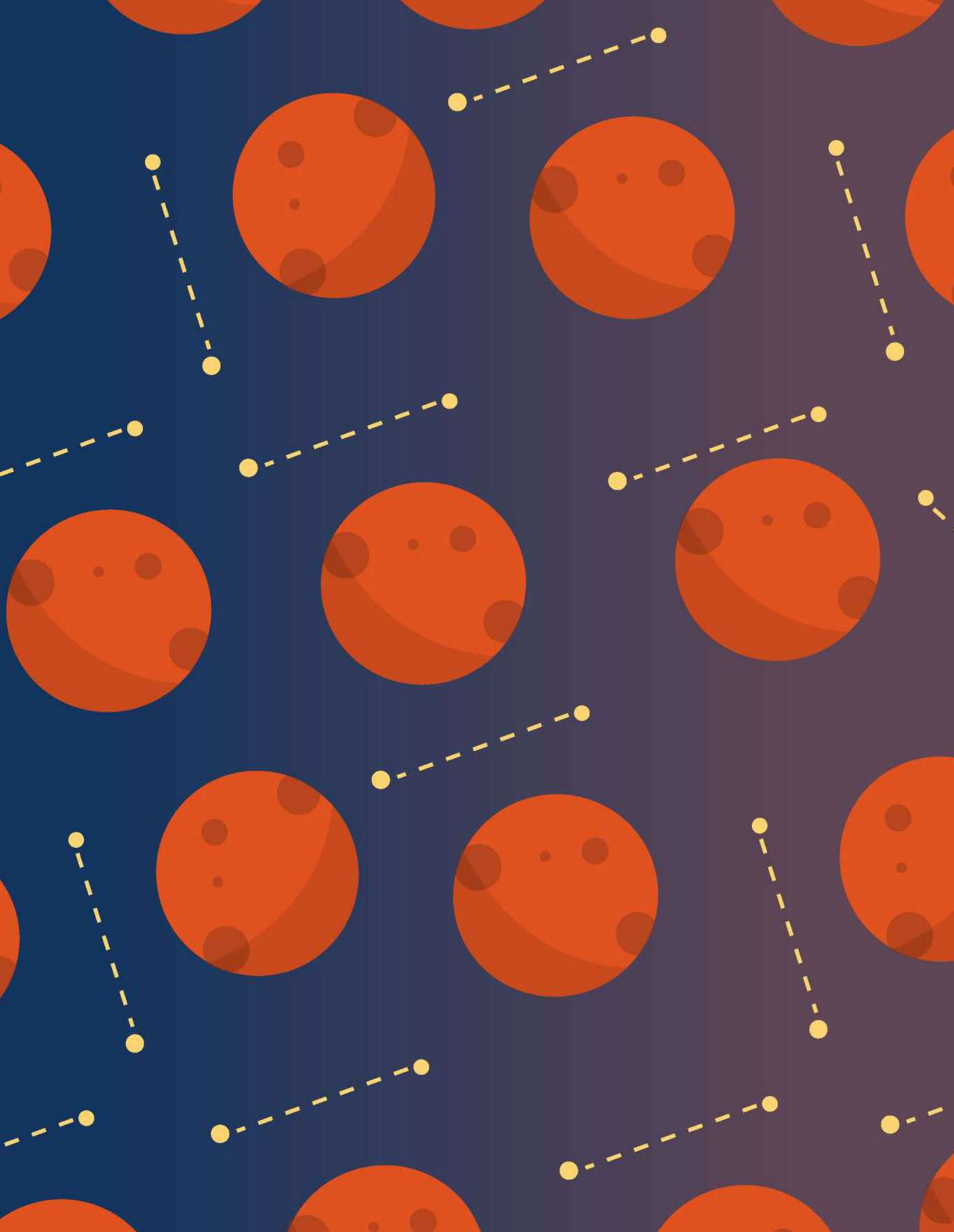
MARS CURSE?
Why is it so hard to land a craft on Mars?

WHY DOES MARS WOBBLE?
What's behind the Red Planet's strange orbital anomaly, and how does it affect spacecraft?

MARS ROVER
Join Perseverance on a trip across the Martian surface

Digital Edition

FUTURE
FIRST EDITION



WELCOME

Is there life on Mars? Or was there, in the distant past? Could there be in the future, in the shape of human beings? Discover the answers to all of these questions and more in the complete guide to everything you need to know about Mars. Find out about its geology, its ancient history and its structure. Marvel at its record-breaking landscape, featuring some of the largest geographical features in the Solar System. Explore its surface, its moons, and the reasons why it wobbles on its axis and is losing its sky. Learn about the probes, robots and rovers we've sent to explore it, and why landing a craft on Mars successfully is such a challenge. Meet some of the scientists and would-be Mars explorers who are looking at the challenges Mars presents, and how they can be overcome, in the hope of one day setting foot on the Red Planet.


FUTURE

EVERYTHING YOU NEED TO KNOW ABOUT MARS

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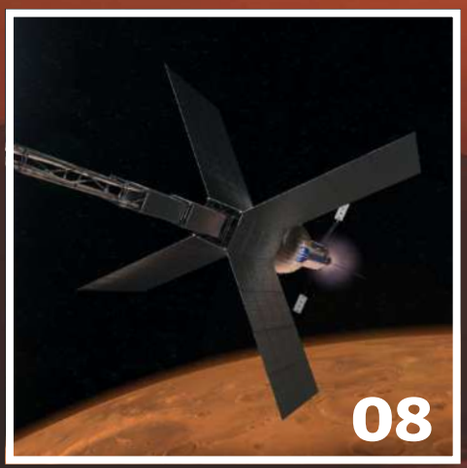

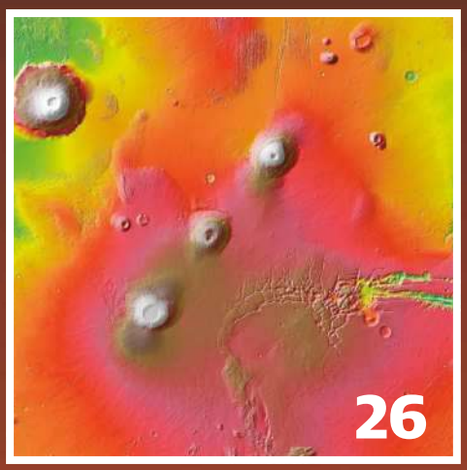

PLANET PROFILE

MARS

THE RED PLANET HAS A HOST OF NEW ROBOTS INVESTIGATING IT

Across the gulf of space, no other planet has fired humanity's imagination so much as the Red Planet, and it has frequently been associated with violence, war and death. To the ancient Sumerians it was Nergal, a god of war and plague who presided over the netherworld. In Mesopotamia it was the 'star of judgement of the fate of the dead'. The Chinese associated it with the element fire, while for the people of the Tiwi Islands off the coast of Australia the planet was one of the four wives of the Moon Man, who followed the path of the Sun Woman through the sky – the other wives were Mercury, Jupiter and Venus. The planet was a familiar sight to the astronomers of ancient Egypt, Babylonia, Rome – where Mars was the god of war – and Greece, where Aristotle noticed that the planet vanished behind the Moon during an occultation, proving it was farther away.

Following the invention of the telescope in the 17th century, Mars could be observed in greater detail, and Christiaan Huygens was able to observe Syrtis Major – which he thought was a plain, but we now know to be a volcano – the first surface feature seen on another planet, in 1659. He was also able to measure Mars' day length as 24 hours and 30 minutes – only seven minutes short of the true value.

It would be another 312 years before a human-made spacecraft would touch down on Martian soil, with the Soviet Union's Mars 3 lasting 110 seconds on the surface and managing to transmit only part of a single image that showed no detail. There would be several more failures until NASA's Viking 1 touched down in 1976 and operated for over six years. Exploration of the planet has continued, and right now there are three operational rovers on its surface. Curiosity and Perseverance are from the US, while Zhurong hails from China. These missions are the lucky ones. There have been a spate of failed missions from the USSR, US, UK and Japan – from rocket failures and solar panels failing to open to a mix-up between the units of measurement used in America and the metric system used by most of the rest of the world, which caused NASA's Mars Climate Orbiter to either burn up or skip off the Martian atmosphere and into deep space in 1999.

Human missions to Mars have been a dream since the earliest days of space exploration. In 2004 the Vision for Space Exploration announced by US president George W. Bush called for a crewed mission to the Moon in 2020 as a stepping stone to Mars. In 2007 NASA administrator Michael D. Griffin said the agency aimed to put a person on Mars by 2037. The Journey to Mars plan, formulated by NASA in 2015, uses the ISS and an asteroid captured in 2020 to test deep-space habitation facilities. That phase is behind schedule, but the ISS phase is underway and set to last until 2024. Humans on Mars in the 2030s is still NASA's goal.

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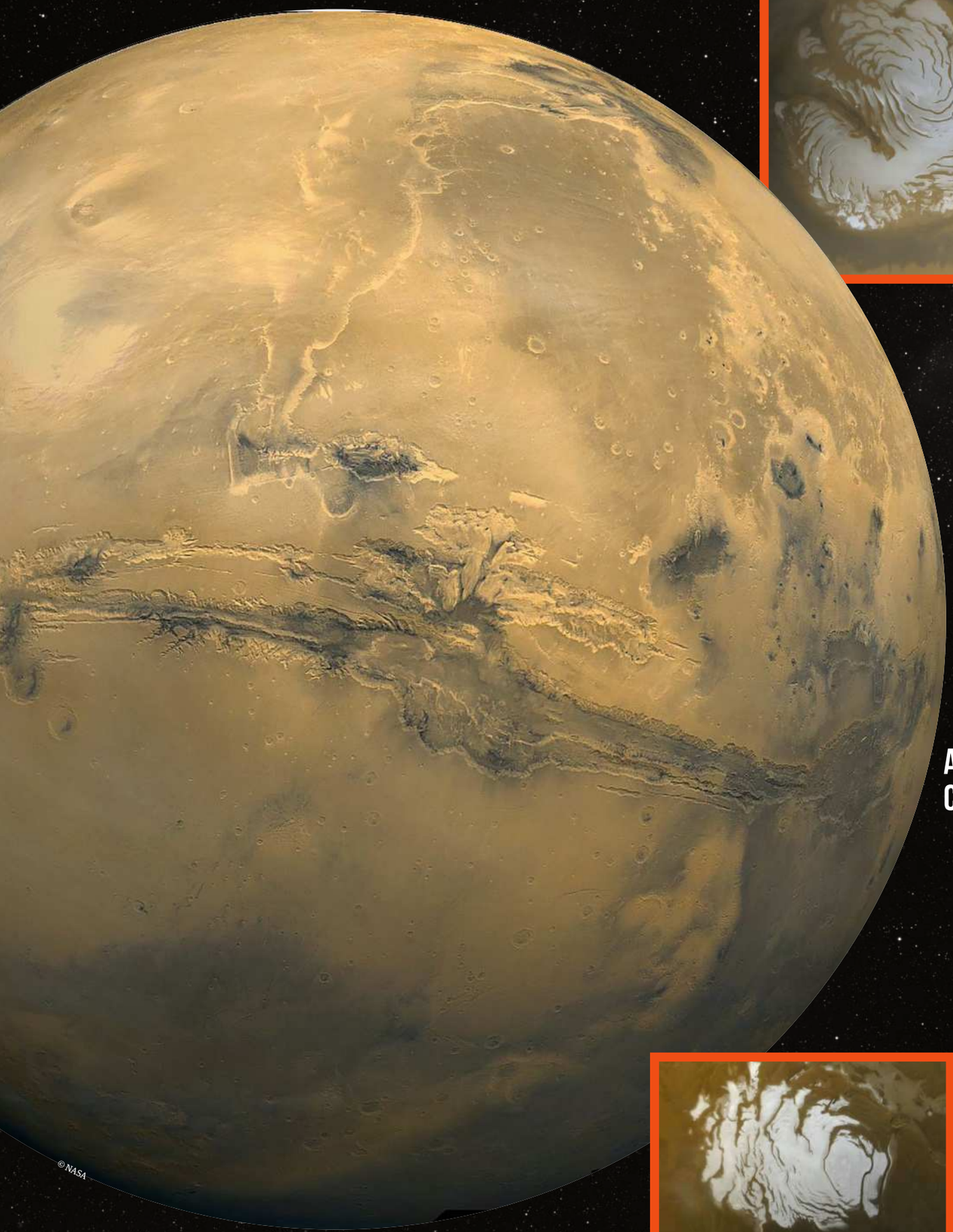
Left: Mars Pathfinder explores the rocky surface of the Red Planet



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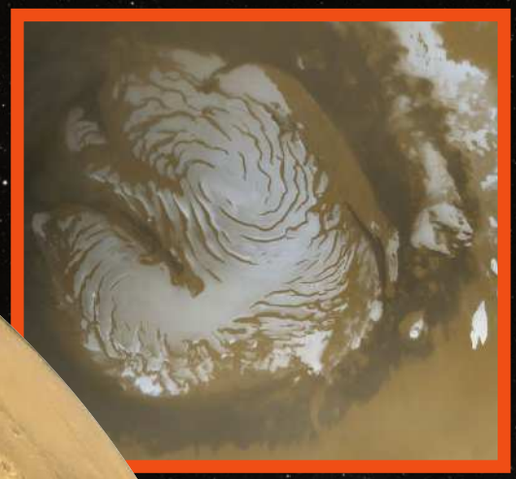

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Above: Mars' north pole, taken by the Mars Global Surveyor

Below: Mars Global Surveyor image of ice at the south pole

ATMOSPHERIC COMPOSITION

95%
CARBON DIOXIDE

2.6%
MOLECULAR NITROGEN

1.9%
ARGON

0.16%
MOLECULAR OXYGEN

0.06%
CARBON MONOXIDE

0.03%
WATER VAPOUR

© NASA/JPL

NEWS FROM MARS

RENEWABLE ENERGY ON MARS

Renewable power is a little bit tricky on Mars, which is farther from the Sun, has dust storms and has no tides. What it does have, however, is wind, and so scientists from Delft University of Technology have come up with the excellent idea of designing robots to fly huge power-generating kites in the Martian atmosphere. "Despite the low density of the Martian atmosphere, wind speeds are high enough to make wind energy competitive with nuclear power in terms of power produced per unit mass," the scientists wrote in a research paper. One kite could generate 127 megawatt-hours of energy per year, the scientists say, enough to power five households in the US.

The assembly, which will also have solar panels – though Mars gets only 43 per cent of the sunlight we enjoy on Earth – will catch the wind and be reeled out, performing a series of tacking manoeuvres to maximise its speed and pulling force. This is all controlled by a robot that steers the wing-like kite, changing its angle of attack. Once the cable is pulled out, the kite can be dropped to minimise the pull as it's reeled back in, ready to fly again.

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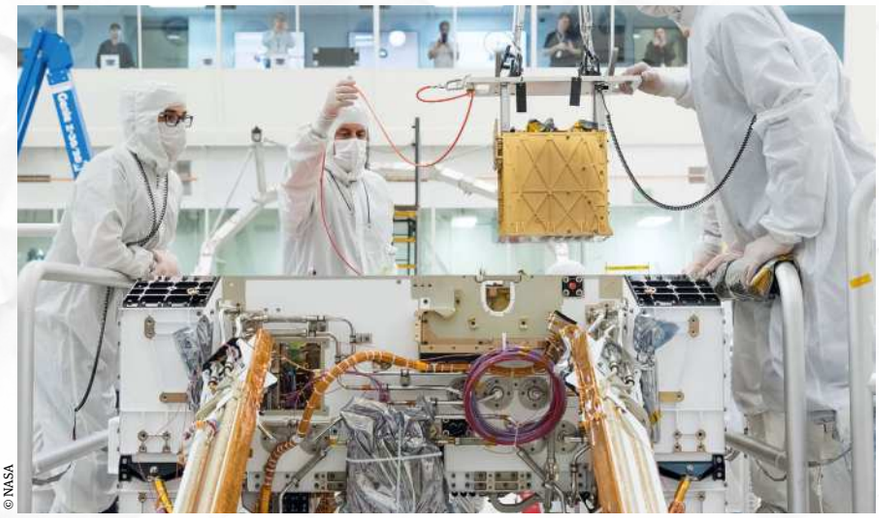

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OXYGEN ON MARS

The atmosphere on Mars is thin and not conducive to effective human breathing. It's a hostile environment, and any astronauts who explore there will need to take their own oxygen. If humans are to build an outpost on the planet, however, they need a way of generating their own oxygen, which is also a critical component of rocket fuel. NASA estimates that to get four astronauts back from Mars would take about 25 tonnes of the gas.

Enter the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), carried aboard NASA's Perseverance rover. This uses 300 watts of power to heat carbon dioxide from the Martian atmosphere, where it strips the oxygen atoms away from the carbon and sends the resulting carbon monoxide back outside. During its first test in April, it created just over five grams of oxygen in an hour, which is about ten minutes of breathing for an astronaut. MOXIE is just a demonstrator, but larger, more powerful versions of it could one day produce enough oxygen for a colony.

INGENUITY WOBBLES, BUT FLIES ON

The small robotic helicopter carried by NASA's Perseverance rover, named Ingenuity, made its sixth flight across the Martian surface near the end of May 2021, but it was a flight marked by control disruptions and power spikes.

The helicopter was asked to climb to ten metres (33 feet) above the surface before flying to the west to take stereoscopic images of a region of interest there. It had been flying for 54 seconds when a glitch was noticed in the stream of images coming from the navigation camera. Only one image was lost, but this led to the following images being delivered with inaccurate timestamps. Ingenuity uses an algorithm to navigate that uses both visual data about where things are and timestamps to tell it when it saw them.

As a result, Ingenuity began adjusting its velocity and tilting back and forth in an oscillating pattern, and this behaviour persisted for the rest of the flight. It encountered roll and pitch excursions of more than 20 degrees, large control corrections and spikes in power consumption. Despite this, the robotic aircraft was able to land within five metres (16.5 feet) of its intended location.

© NASA

NUCLEAR ROCKETS

Above: Illustration of a Mars transit habitat and nuclear propulsion system that could one day take astronauts to Mars

All this talk of oxygen and energy is all well and good, but before you can start deploying these technologies on Mars you've got to get there. NASA has explored the Solar System using a range of chemical rockets and gas-fuelled manoeuvring systems, but is investigating two methods of nuclear propulsion to speed humanity to the Red Planet.

The first is nuclear electric propulsion, otherwise known as the ion drive, which supplies low thrust over a long interval to gradually build high acceleration. The other is nuclear thermal propulsion, which provides high thrust and twice the propellant efficiency of chemical rockets. NASA is looking into preliminary reactor design concepts for such a rocket, which heats a fluid, usually liquid hydrogen, in a nuclear reactor. Once it reaches a high enough temperature, the fluid expands through a rocket nozzle to create thrust.

Nuclear thermal propulsion has been on NASA's radar for more than 60 years. Research on the subject once concentrated on fission reactors, but these came with a number of problems, notably that no one wanted a flying fission reactor with even a chance of exploding over their heads. Recent research has moved to nuclear fusion power, and such a rocket could be constructed in orbit as an additional safety measure. Nuclear propulsion could enable missions to Mars at times when the planet is not favourably positioned relative to Earth, and could cut the round trip time of a crewed mission to just two years.

EVOLUTION OF THE RED PLANET

- **Date:** 4.57 billion years ago
  Activity: Mars was part of the same protoplanetary disc as the other planets, swirling around the nascent Sun.
- **Date:** 4 billion years ago
  Activity: The Late Heavy Bombardment scarred Mars' surface – these craters can still be seen today.
- **Date:** 4 billion years ago
  Activity: Mars was hit by a body the size of Pluto, creating the smooth Borealis Basin that covers 40 per cent of Mars.
- **Date:** 3.8 billion years ago
  Activity: Substantial amounts of liquid water on the surface began to dry up due to the loss of the planet's magnetic field and its atmosphere.
- **Date:** 3.3 billion years ago
  Activity: Olympus Mons, a huge volcano, formed as part of a period of enormous geological activity.
- **Date:** 237 years ago
  Activity: Astronomer William Herschel declared Mars would offer "a situation in many respects similar to ours".
- **Date:** 144 years ago
  Activity: Asaph Hall discovered Phobos and Deimos, the Martian moons.
- **Date:** 50 years ago
  Activity: Humans started dropping craft and robots onto the surface, but many of these fail.

MARS BY NUMBERS

15%
Mars is 15 per cent of Earth's volume

8 METERS
There is eight metres of permanent frozen CO_2 at the south pole

38%
Its gravity is 38 per cent of Earth's

70%
The polar caps are 70 per cent water ice

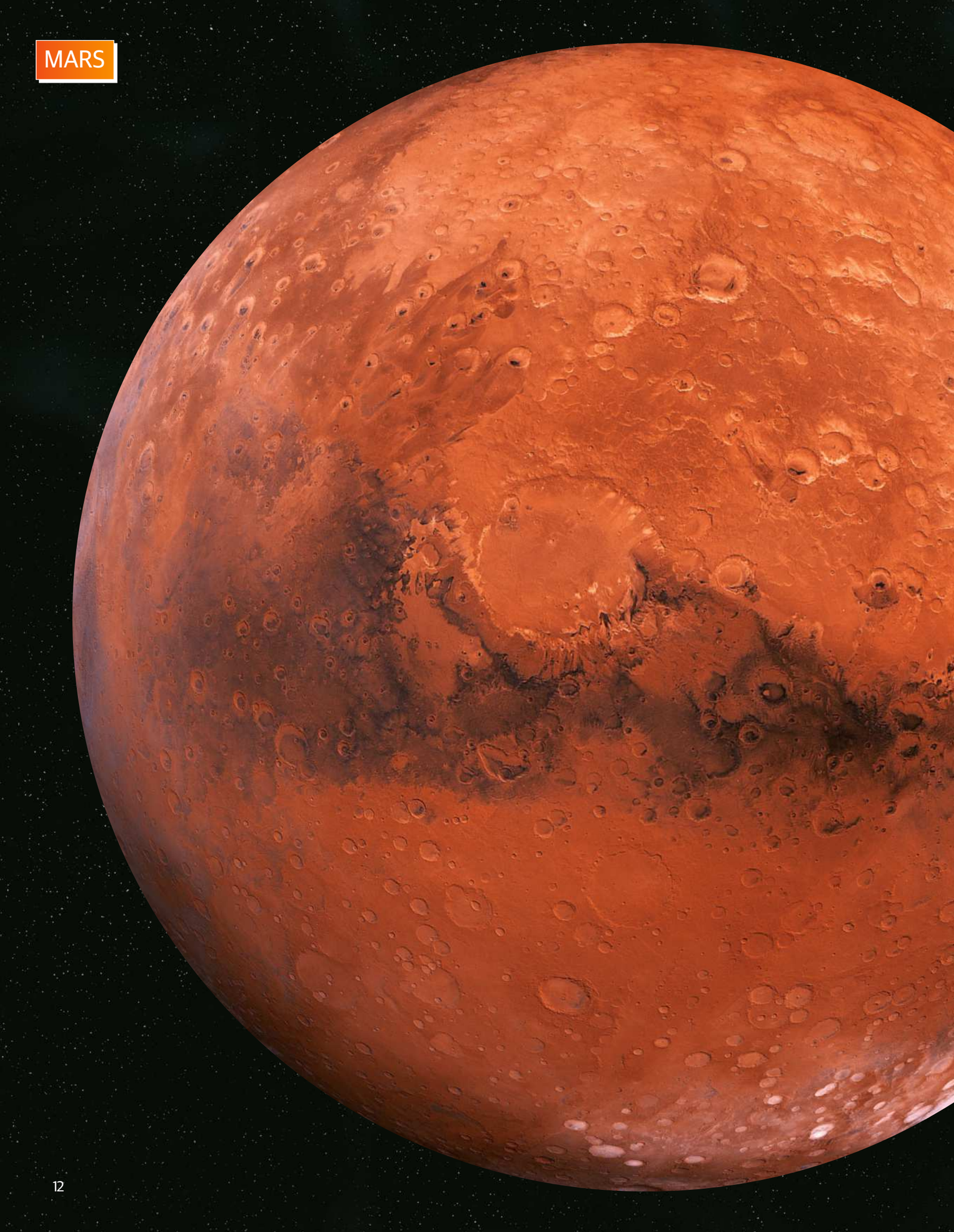
OLYMPUS MONS
The tallest mountain of any planet, it's 2.5 times the height of Everest above sea level

11%
Mars has 11 per cent of Earth's mass

7.7
Its soil pH is 7.7, which is slightly alkaline

Left: Olympus Mons is a dormant shield volcano, the biggest in the Solar System

MARS



ALL ABOUT...
MARS

THE FOURTH PLANET FROM THE SUN AND THE SEVENTH LARGEST, THE RED AND VARIED LANDSCAPE OF THIS ONCE EARTH-LIKE PLANET HAS FASCINATED HUMANITY SINCE WE FIRST VIEWED IT IN THE NIGHT SKY. LET'S EXPLORE JUST WHY THIS PLANET HOLDS SUCH ALLURE

Words Shanna Freeman

MARS

Because it appears red due to the rust on its surface, Mars has long been called The Red Planet. Its 'bloody' appearance is also why it was named after the Roman god of war. But that potentially scary appearance hasn't kept us from wanting to learn more about it. Mars formed about 4.6 billion years ago, along with the other planets in the Solar System. After the initial formation, Mars was bombarded at length by meteors, which caused its heavily cratered appearance. As the planet separated into layers, molten rock in the mantle pushed through the crust, resulting in volcanic activity. The activity released a lot of heat from the core, which led it to cool down very quickly. Atmospheric water likely froze, causing flooding, but the lack of atmospheric pressure meant that water was swirled away by solar winds. Eventually Mars settled down into the dusty and dry planet we've been watching since ancient times.

We can easily see Mars from Earth without a telescope, and it's actually easier to see when it's further away in its orbit because our atmosphere gets in the way. We've sent lots of probes to the planet, including the 2012 addition of NASA's Curiosity rover. So far we've discovered that Mars is so much like the Earth, but also so very different. It is a terrestrial planet and has almost identical geographical features and a similar axial tilt (which results in seasons). It also has basically no atmosphere, no liquid water and wildly fluctuating temperatures on the surface. If there are any Martians lurking around, they have to be a hardy group – and so far they've eluded detection.
Mars is red, but not all red. Although we can see the planet, we can't actually see any of its features. We do, however, see albedo features, areas of light and dark. While most of the planet is red there are also bright white areas at the poles, some upland areas, and also in the form of ice clouds. The darker spots are places where the intense wind has removed the ruddy dust to expose basaltic volcanic rock.

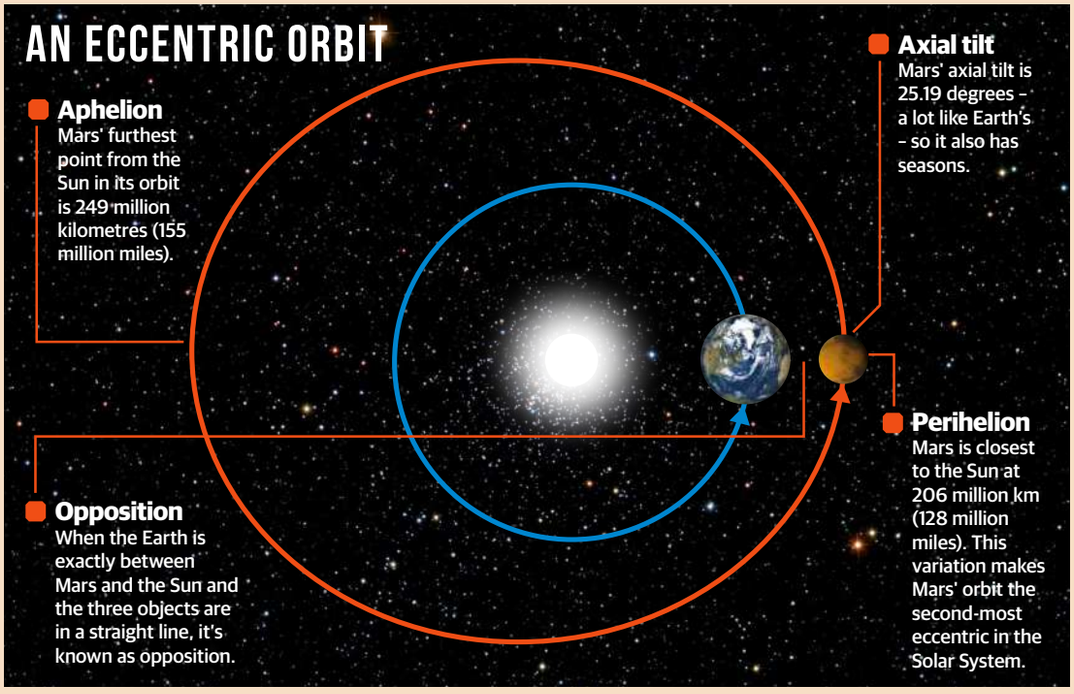
Mars is the fourth planet from the Sun in the Solar System, right between the Earth and Jupiter.
Size-wise it is the second-smallest planet, behind Mercury. Despite all of the Earth comparisons, it's about half the diameter of Earth, and much less dense. In fact, its mass is about 11 per cent that of Earth's and its volume is about 15 per cent. But because there are no oceans on Mars, the smaller planet has the same amount of dry land as the Earth does.

The planet's average distance from the Sun is about 228 million kilometres (142 million miles). It takes 687 Earth days to orbit the Sun, but Mars has a very eccentric elliptical orbit. Its eccentricity is 0.09, which is the second-most eccentric in the Solar System behind Mercury (the Earth has an orbital eccentricity of 0.0167, which is almost a circle). But we believe that Mars once had a much rounder orbit – it has changed due to gravitational influences from the Sun and other planets. Rotation-wise, a Martian day is just a bit longer than an Earth day at 24 hours, 39 minutes and 35 seconds. Mars is also tilted 25.19 degrees, close to the Earth's axial tilt of 23.44 degrees. That means depending on where the planet is in its orbit around the Sun, different hemispheres will be exposed to more light – better known as seasons. They aren't seasons like we know them, which are fairly equal in length on most parts of the surface of Earth. On Mars, spring is seven months long, for example, while winter is only four. The seasons are longer because the year is longer – Mars is further away from the Sun than the Earth – but they vary because of the eccentricity of Mars' orbit.

Mars also has two natural satellites, or moons – Phobos and Deimos. Both are potato-shaped and may have been asteroids that got trapped by Mars' gravitational pull or they could have formed from material ejected from Mars during impact. The planet might also have other tiny satellites that have yet to be discovered.

Over the years science fiction has often portrayed Mars as a sister planet to Earth and although there are many key differences – the small matter of life, for example – a true understanding can often be reached by making the right comparisons. NASA has referred to Earth as 'one of the best comparative laboratories' and the study of Mars can provide

AN ECCENTRIC ORBIT



Aphelion
Mars' furthest point from the Sun in its orbit is 249 million kilometres (155 million miles).

Axial tilt
Mars' axial tilt is 25.19 degrees – a lot like Earth's – so it also has seasons.

Perihelion
Mars is closest to the Sun at 206 million km (128 million miles). This variation makes Mars' orbit the second-most eccentric in the Solar System.

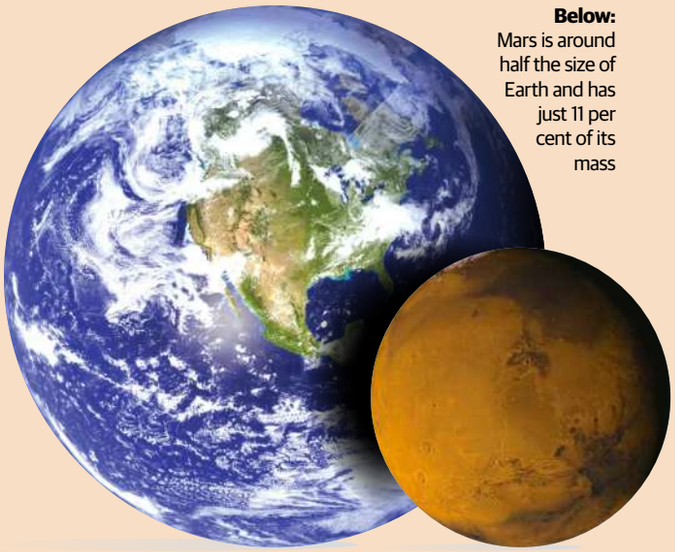
Opposition
When the Earth is exactly between Mars and the Sun and the three objects are in a straight line, it's known as opposition.

THE PLANETS IN RELATION TO THE SUN

All figures = million miles from Sun

Mars lies 228 million km (142 million miles) from the Sun and 225 million km (140 million miles) from Earth

"BECAUSE THERE ARE NO OCEANS ON MARS, IT HAS THE SAME AMOUNT OF DRY LAND AS THE EARTH DOES"

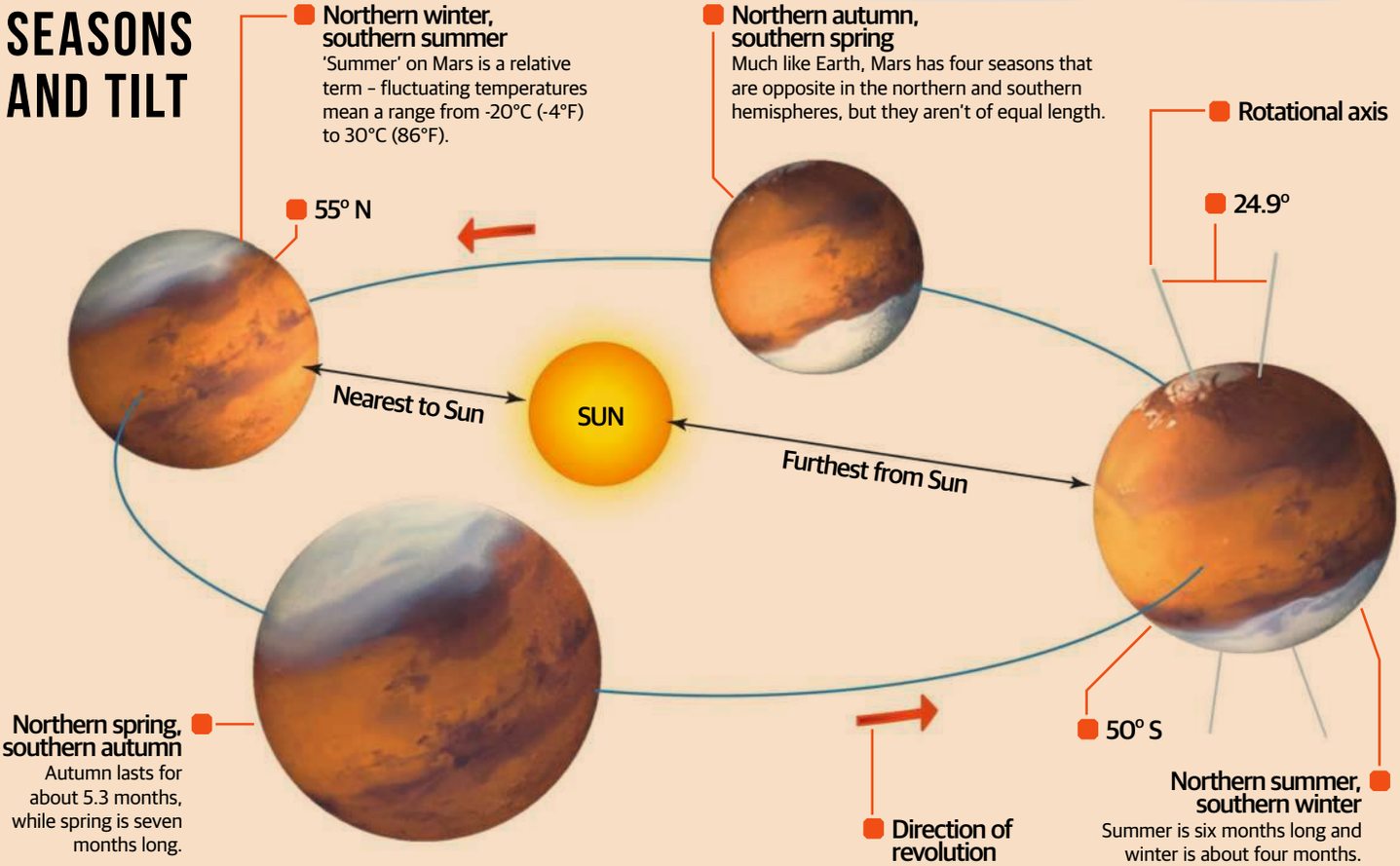


Below: Mars is around half the size of Earth and has just 11 per cent of its mass

scientists with a control set for studying the potential for life beyond our world.

As mentioned, the chief of these differences is the size of the planet: Mars is a smaller world with 53 per cent the diameter and just 11 per cent the mass of Earth. The surface gravity on the Red Planet is 38 per cent that of Earth's, meaning that a human who can jump one metre (3.3 feet) on Earth could jump 2.6 metres (about nine feet) on Mars. As well as the similar land surface area the atmospheric chemistry is relatively similar especially when Earth and Mars are compared to other planets in the Solar System. Both planets have large polar ice caps made primarily of water ice, according to current thinking. Other similarities include a similar tilt in their rotational axis, which causes strong seasonal variability on the planets' surfaces.

SEASONS AND TILT



THE MOONS OF MARS

Phobos

Phobos is the bigger of Mars' two satellites, and orbits the closest. In fact, it orbits closer to its planet than any other satellite in the Solar System. The distance from the moon to the planet is about 6,000km (3,700 miles) from the surface. Phobos has a radius of about 11km (seven miles) and is irregularly shaped and non-spherical. Its biggest feature is a large impact crater named Stickney, which has a diameter of about 9km (5.6 miles).

Deimos

Deimos is much farther from Mars than Phobos at around 23,400km (14,600 miles) away. It's also significantly smaller, with a radius of around 6km (four miles), and takes much longer to orbit Mars at 30.4 hours. Deimos, like Phobos, is not at all spherical. It has a very porous surface, and also features large craters relative to its size, with the two largest being Swift and Voltaire. Both craters are believed to be between 1 and 3km (0.6 and 1.9 miles) in diameter.

MARS INSIDE AND OUT

Its make-up may resemble Earth's, but Mars is a very different planet

Mars is a terrestrial, or rocky, planet – just like Earth. It also has a differentiated internal structure, meaning that there's an outer crust, a mantle and a core. However, that structure isn't exactly like the Earth's.

At the centre of the planet, Mars' core is believed to be between around 3,000 and 4,000 kilometres (1,850 and 2,500 miles) in diameter. It's mostly made up of iron, with nickel and traces of other elements, such as sulphur. Scientists believe that the core is mostly solid but may also contain a fluid layer. There is no magnetic field generated at the core, but Mars may have had a magnetic field in the past. There are currently areas of magnetisation at different places on the planet's surface. The differentiation process, in which heavier metals such as iron sunk through to the core while Mars was forming, may be responsible for the ending of its magnetic field.

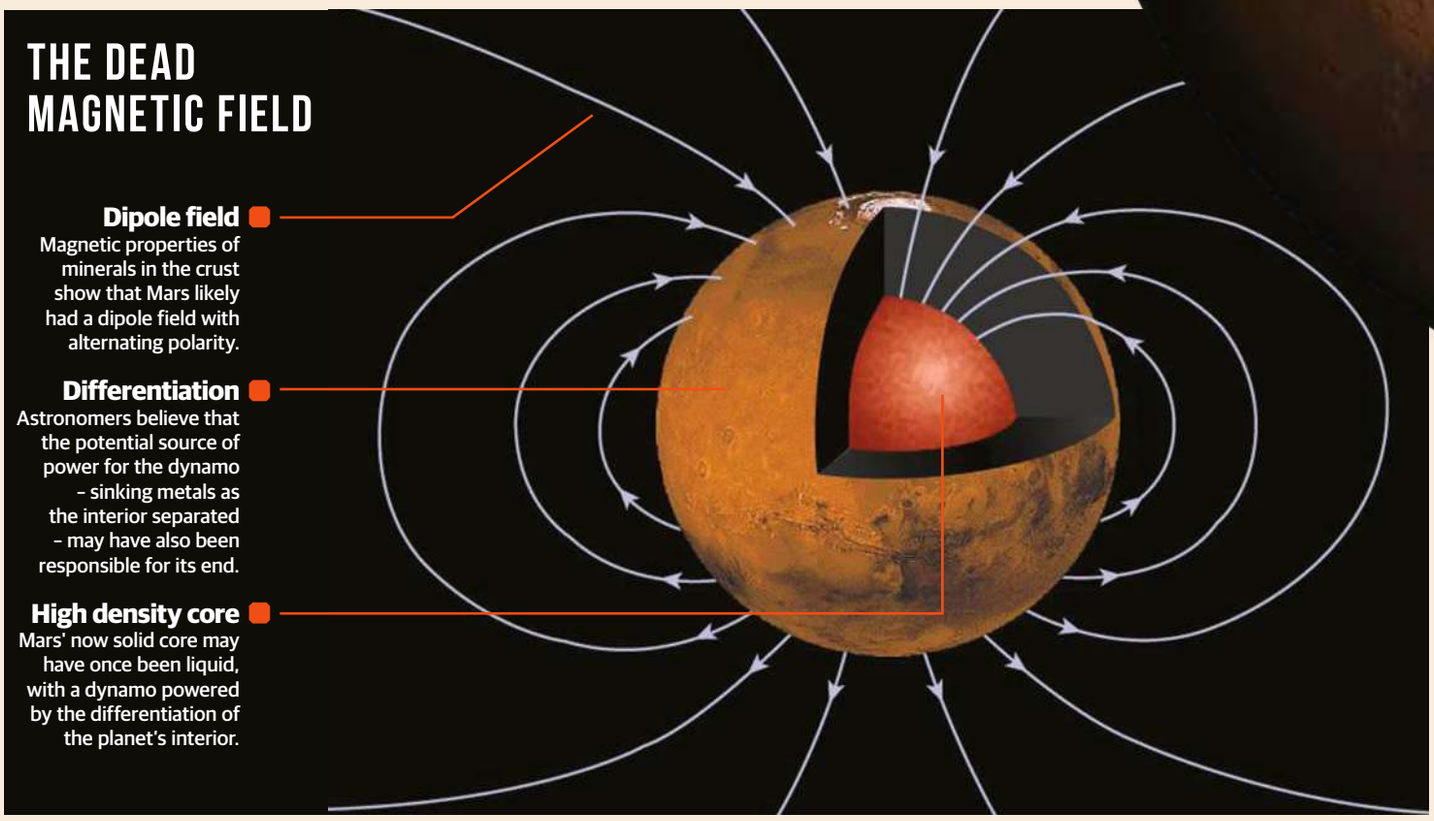
Atop the core lies Mars' silicate mantle, which is between 1,300 and 1,800 kilometres (800 and 1,100 miles) thick. Volcanic activity on the planet's surface originated here, resulting in the huge volcanoes, lava flows and other features that can be found on Mars' surface – however, the most recent volcanic activity likely took place about 2 million years ago. That may not be particularly recent by our standards, but it's fairly recent when it comes to Mars' history. These were lava flows, however; the volcanoes appear to be extinct.

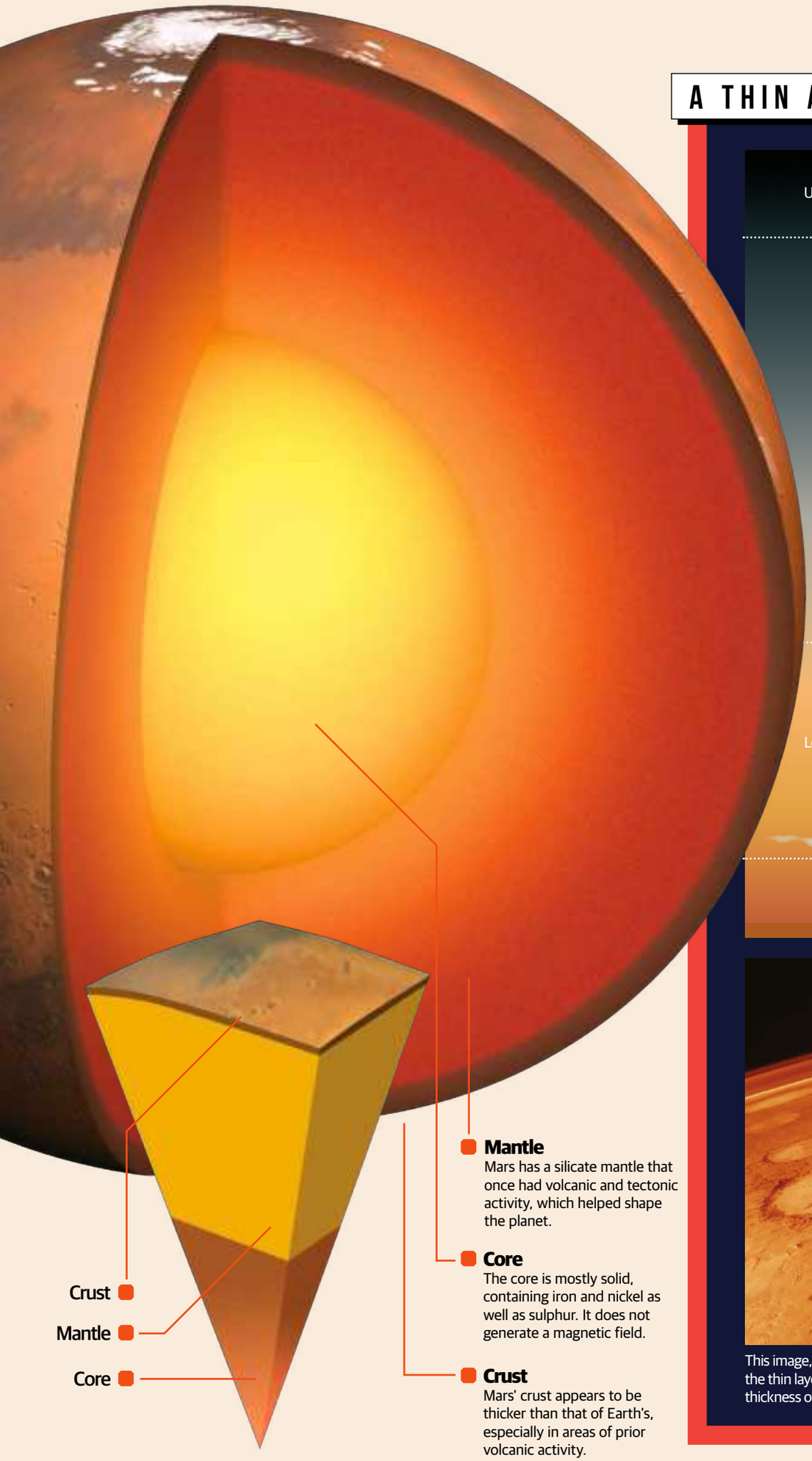
Finally, there's the crust, which is about 25 to 80 kilometres (16 to 50 miles) thick. It contains oxygen, silicon, iron, calcium and other metals. The high concentrations of iron and oxygen result in rust – iron oxide – which is responsible in part for the red appearance of Mars. At its thickest the crust is more than twice as thick as the Earth's crust. The surface is covered with regolith in many places – a loose conglomerate of broken rocks, dirt and dust that sits lightly on the surface.

There isn't much atmosphere – the solar wind strips away molecules and carries them out into space. What little atmosphere is left is made up of about 95 per cent carbon dioxide, three per cent nitrogen, two per cent argon with trace gases as well.

"THE SOLAR WIND STRIPS AWAY MOLECULES AND CARRIES THEM OUT INTO SPACE"

THE DEAD MAGNETIC FIELD



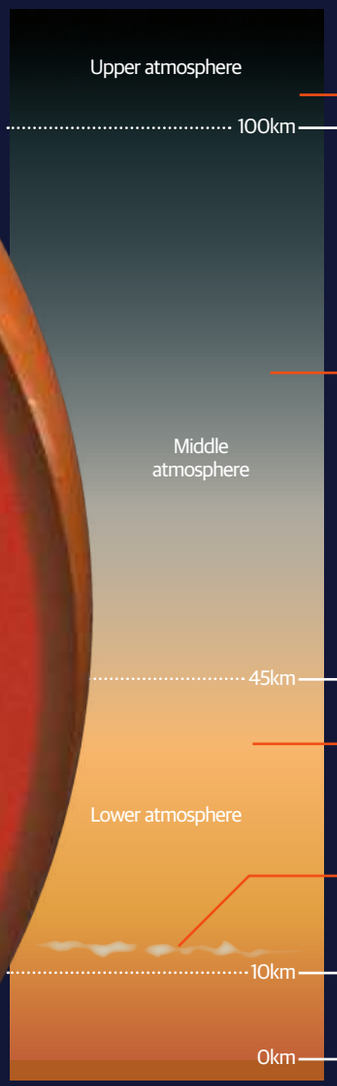


Mantle
Mars has a silicate mantle that once had volcanic and tectonic activity, which helped shape the planet.

Core
The core is mostly solid, containing iron and nickel as well as sulphur. It does not generate a magnetic field.

Crust
Mars' crust appears to be thicker than that of Earth's, especially in areas of prior volcanic activity.

A THIN ATMOSPHERE



Upper atmosphere
Also known as the thermosphere, this layer is heated by the Sun. The lack of a magnetic field means that the gases separate out into space.

Middle atmosphere
In the middle atmosphere, the Martian jet stream swirls the surface dust and gives the sky its orange colour.

Lower atmosphere
The atmosphere contains 95 per cent carbon dioxide, three per cent nitrogen, two per cent argon and traces of elements such as methane.

Thin ice clouds
Strong winds sweeping off Mars' polar ice caps, along with atmospheric sublimation of carbon dioxide, help create these thin ice clouds.

This image, taken by the Viking Orbiter from low orbit, shows the thin layer of Mars' atmosphere – less than one per cent the thickness of Earth's atmosphere

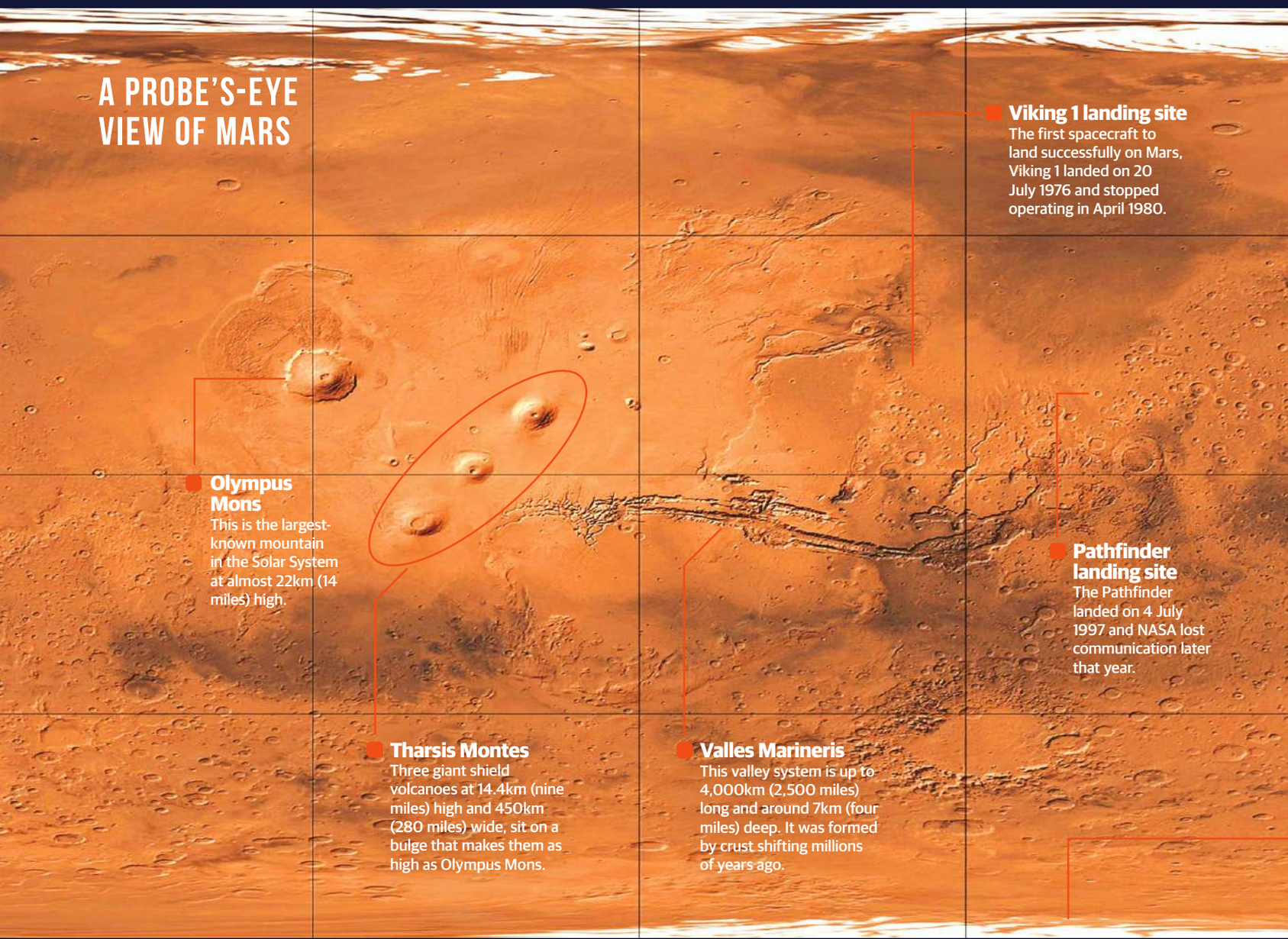
ON THE SURFACE

Mars has a lot of geographical similarities with Earth, but there's a reason why we haven't found life there... yet

Thanks to the many images sent back from various probes, we know that Mars has a lot of interesting geographical features. The biggest one is that Mars has incredibly different northern and southern hemispheres. Most of the northern hemisphere is lower in elevation than the southern one (up to six kilometres or four miles lower). It also has far fewer impact craters, and is much smoother and uniform all over. Finally, the crust on the northern hemisphere appears to be much thinner than the southern hemisphere's. While astronomers aren't sure of the reasons behind this dichotomy, it involves the three main forces that have influenced the planet's surface: volcanic activity, tectonics and impacts.

Some of the most striking features on Mars' surface are its mountains - which are all inactive volcanoes. The western edge of the southern hemisphere contains two different areas - the Tharsis bulge and the Elysium volcanic complex - each of which contain several volcanoes. The Tharsis bulge covers about 25 per cent of the planet's surface and lies seven to ten kilometres (four to six miles) above it. This includes Mons Olympus, a shield volcano that is the largest mountain in the Solar System. Up until a few years ago, scientists were sure that Mars didn't have plate tectonics like Earth.Then we discovered that there are in fact tectonics at work. Not only do features like steep cliffs and the flat walls of canyons show faults at work, but so do the fact that Mars' volcanoes are concentrated in two different areas. The huge valley system known as the Valles Marineris is the deepest in the Solar System and takes up a quarter of the planet's circumference. It's also a plate boundary, with horizontal movement

A PROBE'S-EYE VIEW OF MARS



Viking 1 landing site
The first spacecraft to land successfully on Mars, Viking 1 landed on 20 July 1976 and stopped operating in April 1980.

Olympus Mons
This is the largest-known mountain in the Solar System at almost 22km (14 miles) high.

Pathfinder landing site
The Pathfinder landed on 4 July 1997 and NASA lost communication later that year.

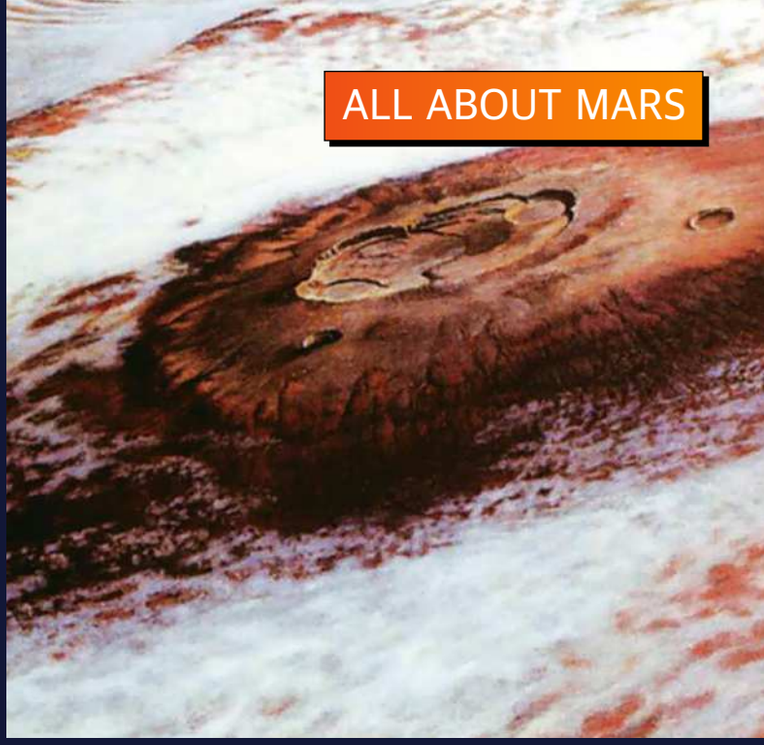
Tharsis Montes
Three giant shield volcanoes at 14.4km (nine miles) high and 450km (280 miles) wide, sit on a bulge that makes them as high as Olympus Mons.

Valles Marineris
This valley system is up to 4,000km (2,500 miles) long and around 7km (four miles) deep. It was formed by crust shifting millions of years ago.

along the plates. With just one known fault as opposed to many on Earth, some believe that Mars' tectonic system is much younger.

Impact craters and basins are prevalent in Mars' southern hemisphere. The Hellas basin is the largest of these at 1,800 kilometres (1,100 miles) in diameter. The largest basins are believed to date back to a period of heavy bombardment about 3.8 billion years ago. They show evidence of erosion and also contain a lot of regolith, or soil deposits. The smaller craters are younger, and look a lot like the Moon's impact craters.

Mars has many different types of craters thanks to erosion, deposits and volcanic activity. They also contain ejecta blankets – flows formed in the soil after an impact melts ice under the planet's surface. Mars is believed to have ice underneath its surface – and there are also ice caps at the poles, the amount of which changes depending on the seasons. Because Mars has a similar tilt to the Earth, it does have four seasons – they're just longer and of varied lengths. Temperatures can get as low as minus 143 degrees Celsius (minus 225 degrees Fahrenheit) at the ice caps in the winter. The ice beneath the surface freezes and melts depending on the temperature. The atmospheric pressure on Mars is much lower than the Earth's, and it's so thin that there is very little to block the surface from the Sun's heat. There are ice clouds, probably caused when the wind kicks up dust, while one of the Red Planet's biggest weather features is dust storms, which can last up to a month.



Despite its thin atmosphere, Mars does have a layer of ice-water clouds, although the blanket lies below the planet's tallest volcano, Olympus Mons. A wave cloud due to ripples in the atmosphere is also visible

North pole
Mars' north pole contains about a third of the ice found in the Earth's Greenland ice sheet.

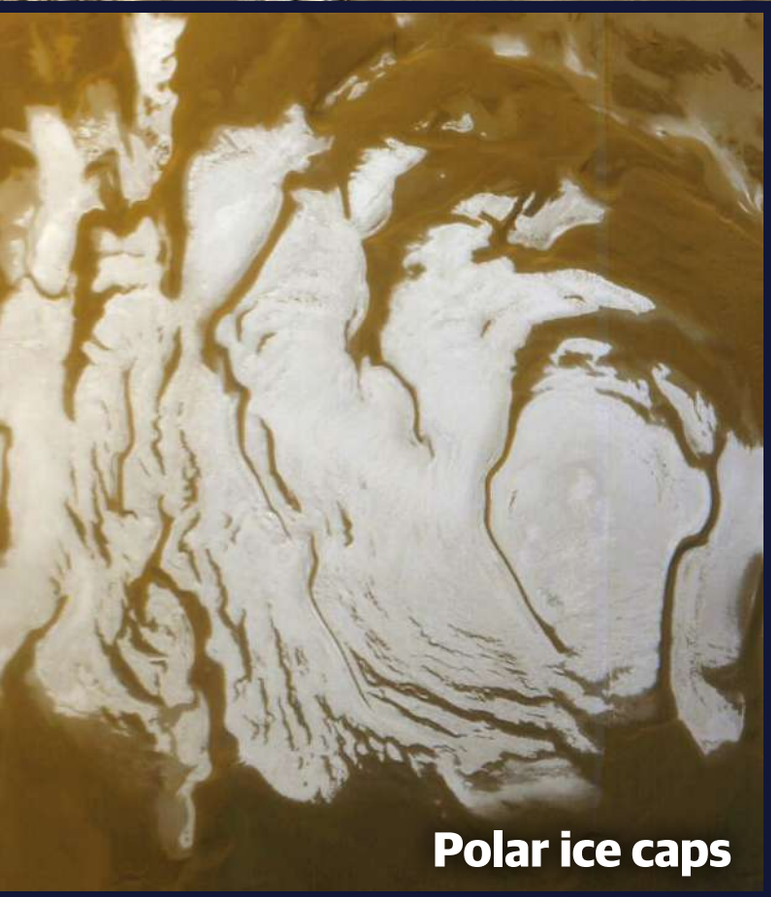
Viking 2 landing site
NASA's Viking 2 landed here on 3 September 1976 and operated until 11 April 1980.

Hellas Planitia
The largest visible impact crater in the Solar System is around 2,300km (1,400 miles) in diameter and 7.2km (4.4 miles) deep.

Spirit rover landing site
NASA's Spirit rover landed on 4 January 2004 and became stuck in soft soil on 1 May 2009. Communication was lost in 2010 and NASA officially ended the mission in 2011.

South pole
The south pole contains enough ice to cover the surface of the planet in a liquid layer up to 11m (36ft) deep.

Olympus Mons



Polar ice caps

CANYONS, CRATERS AND DESERTS

Mars is home to some of the largest planetary features in the Solar System

Olympus Mons
Olympus Mons is the tallest known mountain in the Solar System at 22km (14 miles) high. It's more than twice the size of Mount Everest and is an extinct volcano.

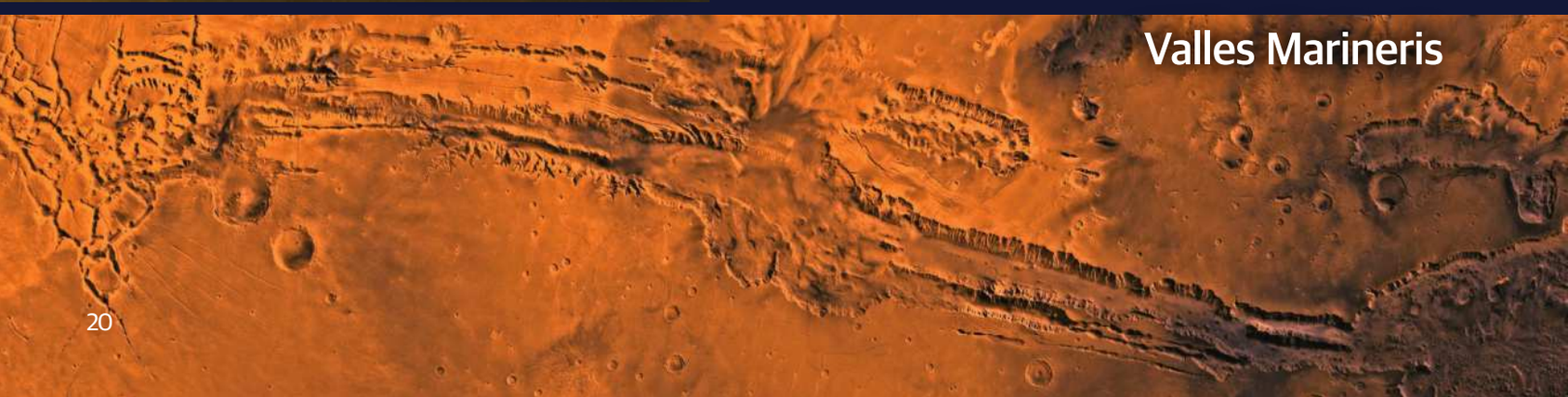
Polar ice caps
This polar ice cap on the southern end of Mars grows and wanes each year depending on the season. It is made up of both water ice and dry ice (frozen carbon dioxide).

Valles Marineris
Valles Marineris is a system of canyons located along the equator of Mars and covers almost 25 per cent of the planet's circumference. It is around 7km (four miles) deep, 200km (124 miles) wide and 4,000km (2,500 miles) long. On Earth, that would be the distance between New York and Los Angeles.

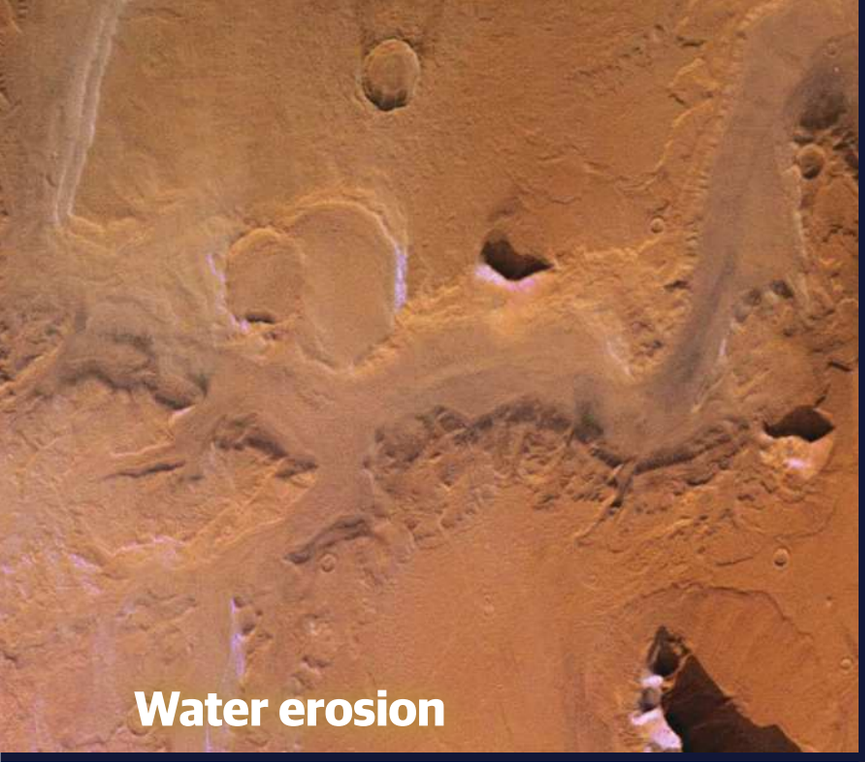
Water erosion
Reull Vallis is one of the valleys on Mars that look as if they may have been carved out by water movement. Many of these valleys contain grooves on their floors that may be rich in ice.

Sand dunes
Regolith – a mix of soil, sand, dust and broken rocks – has drifted into dunes on Mars' surface. We once thought they were stationary, but observations have shown that the dunes actually move due to prevailing winds.

Hellas Basin
The Hellas Basin is one of the biggest impact craters in the Solar System. At 2,300km (1,400 miles) in diameter, it is wider than the state of Texas.



Valles Marineris



Water erosion

Sand dunes

Hellas Basin

MARS BY NUMBERS

Fantastic figures and surprising statistics about the Red Planet

2,300 km

The diameter of Mars' Hellas Basin is the same as the diameter of Pluto

2

Mars has two known satellites: the moons of Phobos and Deimos

271 years and 221 days

How long it would take you to get to Mars from Earth if you could drive there in a car at 97km/h (60mph)

14.5

Travelling at a speed of 14.5 miles per second compared to the Earth's 18.5 miles per second, Mars is slower to orbit the Sun

687 Earth days

A year on Mars is 687 Earth days, while a day on Mars is equivalent to 1.026 Earth days

37.5%

Gravity on Mars as a percentage of Earth's. If you could visit, you could jump three times as high as you can on our planet

EXPLORING MARS

The failure rate in shooting for Mars is high

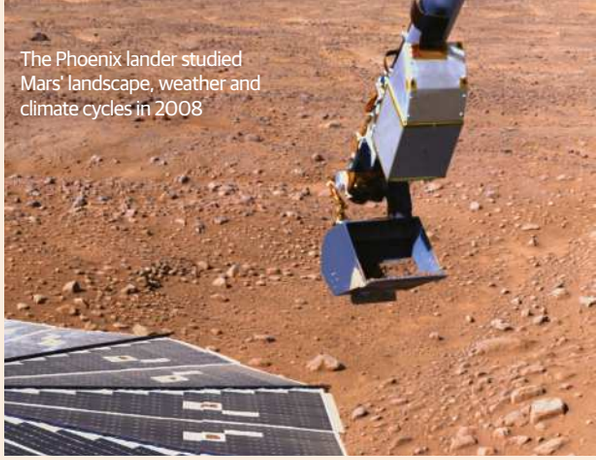
The Soviet Union, not the United States, was the first country to attempt a Mars exploration – but it was unsuccessful. The Mars 1M was just the first of many failed attempts to visit Mars. Since that first attempt in 1960, 43 different spacecraft have tried and only 14 of them completed their missions. Mars 1M had a launch failure, but other probes have been the victims of communication problems, computer malfunctions and even the planet itself. It's been so difficult to get to Mars that some have dubbed the challenge the "Martian curse", and one journalist in the United States jokingly said that there must be a "Galactic Ghoul" hindering our exploration efforts. So why has it proved so difficult to get there?


MSL launches atop a Atlas V rocket on 26 November 2011

It takes a spacecraft about seven months on average to travel the 225 million kilometres (140 million miles) to Mars. Once it reaches the planet, if the orbiter has a lander then it must successfully separate and have the lander touch down gracefully on the surface. And Mars can be unpredictable. Things like dust storms and soft soil have impeded landers, for example. But we do have to remember that most of total failures were early in our space exploration history. While there have been some memorable recent failures, including the 1999 Mars Climate Orbiter, which was pure human error. In that case, a contractor used imperial units instead of metric, which caused the probe's rocket to shut down early and send it crashing down.

Currently there are three orbiters around Mars: the Mars Odyssey and Mars Reconnaissance Orbiter, both from NASA, and the European Space Agency's Mars Express. Sadly after 14 years on the surface, the Opportunity rover was announced inactive when it became swept up in a dust storm in June 2018 but, with Curiosity and Perseverance studying the terrain, humanity continues to explore the red world.

"IT TAKES A SPACECRAFT ABOUT SEVEN MONTHS TO TRAVEL THE 225 MILLION KILOMETRES TO MARS"


The Phoenix lander studied Mars' landscape, weather and climate cycles in 2008

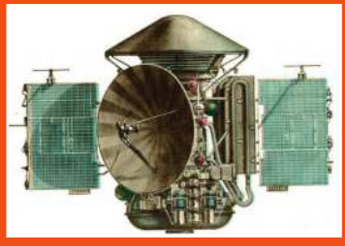

The 120km (75-mile) wide Hadley Crater as imaged by the ESA's Mars Express


The Opportunity rover has been on Mars' surface since 2004

MAJOR MISSIONS

Mars 1M
Oct 1960
These Soviet missions were the first in the quest to explore Mars. Mars 1M No 1 experienced a launch failure on 10 October 1960. Mars 1M No 2 met the same fate.

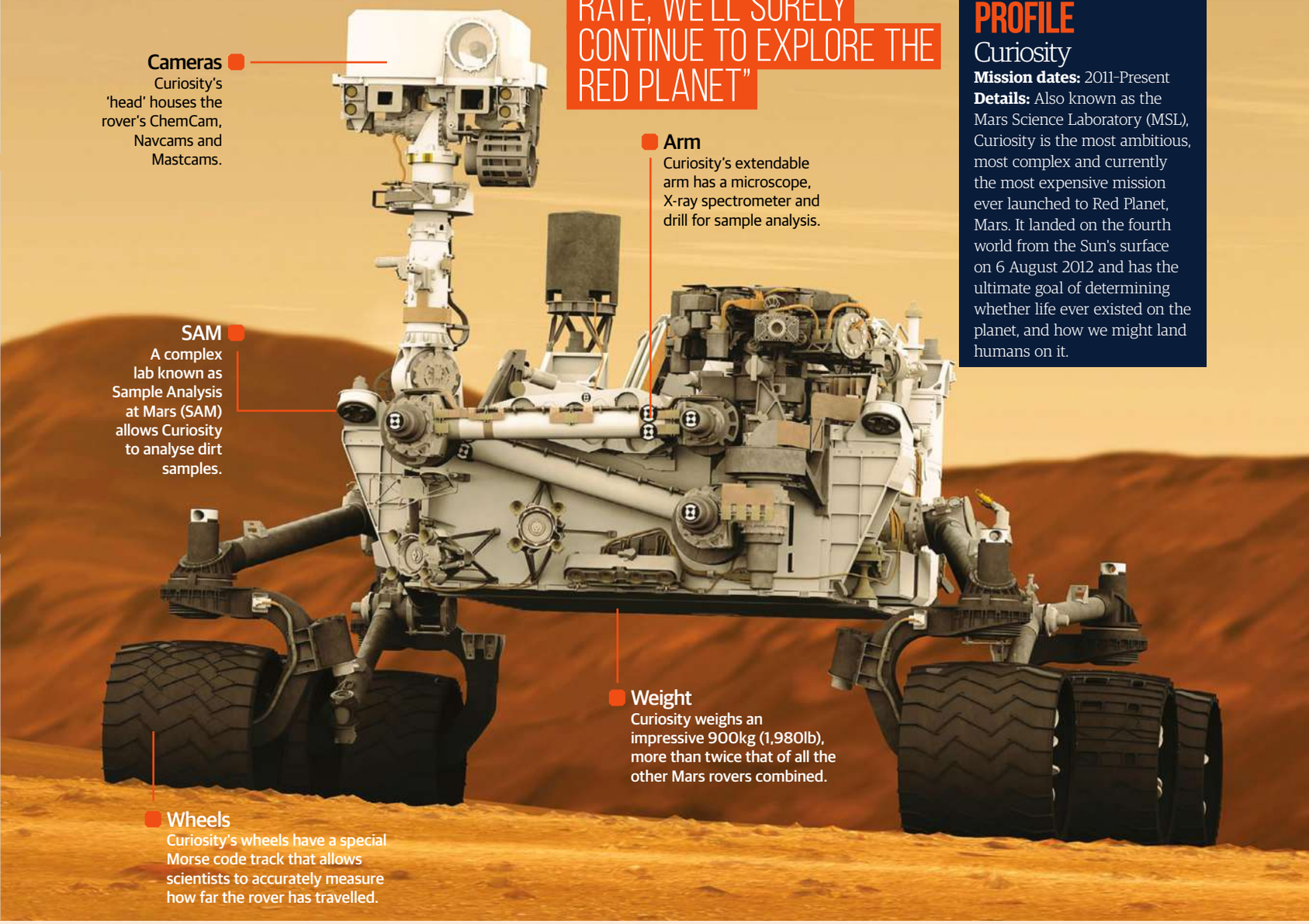
Mariner 4
28 Nov 1964-21 Dec 1967
Mariner 4 performed the first flyby and returned the first colour images of Mars. These were also the first images taken of another planet from deep space.



Mars 2 & 3
19 May 1971-22 Aug 1972
The Soviet-built Mars 2 became the first spacecraft to land – or rather crash – into the surface of the planet. Mars 3 had a soft landing on 2 December 1971.

Viking 1 & 2
20 Aug 1975-13 Nov 1982
Viking 1 landed softly and fully completed its mission. It also held the record for longest Mars mission until the Opportunity rover.

"DESPITE THE HIGH FAILURE RATE, WE'LL SURELY CONTINUE TO EXPLORE THE RED PLANET"



Cameras
Curiosity's 'head' houses the rover's ChemCam, Navcams and Mastcams.

Arm
Curiosity's extendable arm has a microscope, X-ray spectrometer and drill for sample analysis.

SAM
A complex lab known as Sample Analysis at Mars (SAM) allows Curiosity to analyse dirt samples.

Weight
Curiosity weighs an impressive 900kg (1,980lb), more than twice that of all the other Mars rovers combined.

Wheels
Curiosity's wheels have a special Morse code track that allows scientists to accurately measure how far the rover has travelled.

MISSION PROFILE
Curiosity

Mission dates: 2011-Present
Details: Also known as the Mars Science Laboratory (MSL), Curiosity is the most ambitious, most complex and currently the most expensive mission ever launched to Red Planet, Mars. It landed on the fourth world from the Sun's surface on 6 August 2012 and has the ultimate goal of determining whether life ever existed on the planet, and how we might land humans on it.

Mars Polar Lander
3 Jan 1999-3 Dec 1999
The Mars Polar Lander was meant to perform soil and climatology studies on Mars, but NASA lost communication with it and it's believed it crashed.

Mars Express Orbiter
2 Jun 2003-present
The ESA's first planetary mission consisted of the Beagle 2 lander and the Mars Express Orbiter, with the latter still operational today.
xxxxxxxxxxxxx

Beagle 2
2 Jun 2003-19 Dec 2003
The Beagle 2 lander was lost six days before it was due to enter the Martian atmosphere. Attempts were made to contact it, but these ended in failure.

Opportunity
7 Jul 2003-10 Jun 2018
Opportunity was a rover launched shortly after its twin, Spirit, by NASA. It was still going strong up until 2018, when a dust storm silenced it.

Main: Mars hosts the largest volcano in the Solar System: Olympus Mons

ANCIENT MARS WAS ROCKED BY VIOLENT, CLIMATE-CHANGING VOLCANIC ERUPTIONS

SUPERERUPTIONS REGULARLY TORE UP THE SURFACE OF THE RED PLANET BILLIONS OF YEARS AGO

Words Tereza Pultarova

"EACH ONE OF THESE ERUPTIONS WOULD HAVE HAD A SIGNIFICANT CLIMATE IMPACT" PATRICK WHELLEY

A team of geologists has found evidence that large craters visible in satellite images of northern Mars' Arabia Terra region were not created by asteroids, as some had originally believed, but by massive volcanic eruptions that blasted billions of tonnes of gas and molten rock up into the atmosphere. Better known as calderas, these craters are essentially the remnants of once-powerful explosive supervolcanoes, and they have more irregular shapes than their asteroid-created counterparts. But since those powerful eruptions are believed to have taken place some 4 billion years ago, finding conclusive evidence about their nature required forensic methods.

The scientists looked for traces of volcanic ash, modelling how it would disperse after such eruptions and where it would deposit. Then they looked at high-resolution images taken by NASA's Mars Reconnaissance Orbiter to see whether the patterns matched their expectations.

"At that point we said, 'these are minerals that are associated with altered volcanic ash, which has already been documented, so now we're going to look at how the minerals are distributed to see if they follow the pattern we would expect to see from supereruptions,'" said Alexandra Matiella Novak, a volcanologist at the Johns Hopkins Applied Physics Laboratory in Laurel, Maryland. The new research built on Novak's previous studies of volcanic ash deposits in other regions of Mars.

What the researchers found in the images matched the models. The ash spread downwind, eastward from the seven calderas revealed in the Mars Reconnaissance Orbiter images. The deposited ash was traceable thousands of miles away from the craters, with the layer thinning out farther away from the source. "We're actually seeing what was predicted, and that was the most exciting moment for me," said Jacob Richardson, a geologist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, who was part of the research.

The supervolcanoes, likely active during a period of 500 million years some 4 billion years ago, spewed massive amounts of water vapour, carbon dioxide and sulphur dioxide into the atmosphere of Mars, throwing the planet's climate off balance for decades. "Each one of these eruptions would have had a significant climate impact – maybe the released gas made the atmosphere thicker, or blocked the Sun and made the atmosphere colder," said Patrick Whelley, a geologist at Goddard. "Modellers of the Martian climate will have some work to do to try to understand the impact of the volcanoes."

The last supervolcano eruption on Earth took place 76,000 years ago in Sumatra, Indonesia. But terrestrial calderas, dozens of miles wide, are spread around the globe in known tectonically active regions, where the majority of smaller but still active volcanoes also reside today.

The strange thing about the Martian Arabia Terra, however, is the fact that it doesn't show traces of smaller volcanoes. The scientists speculate that calderas on Earth may have been eroded over billions of years or moved around the globe with the shifting continents. These types of explosive volcanoes could also exist in regions of Jupiter's moon Io, or could have been clustered on Venus.

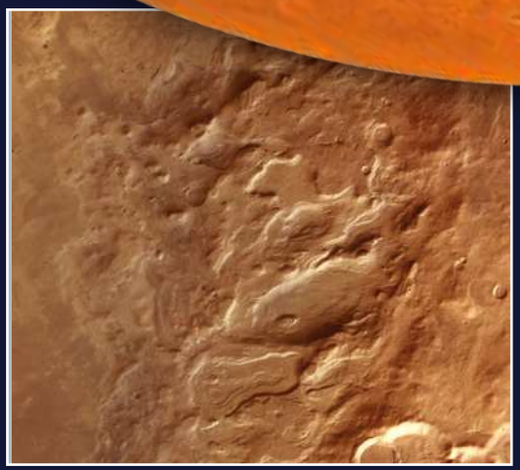
Earlier this year, scientists from the Planetary Science Institute in Tucson, Arizona, found evidence that Mars might still be volcanically active today. However, most of the Red Planet's volcanic activity occurred in the era of the supervolcanoes some 4 billion years ago. Mars' 21.9-kilometre (13.6-mile) high Olympus Mons, the biggest volcano in the Solar System, is believed to have last erupted about 25 million years ago.

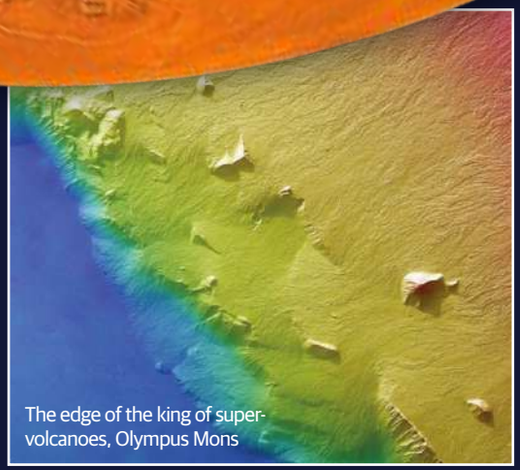
© Getty

10 WONDERS OF MARS

FIRST TIME ON MARS? JOIN US AS WE TOUR SOME OF THE BIGGEST, STRANGEST AND MOST FASCINATING WONDERS THE RED PLANET HAS TO BEHOLD

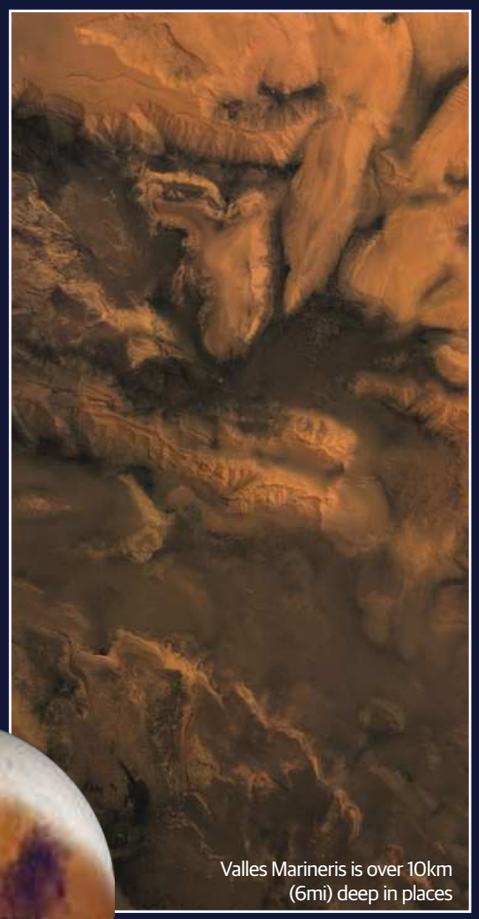
Words Ben Biggs and Giles Sparrow





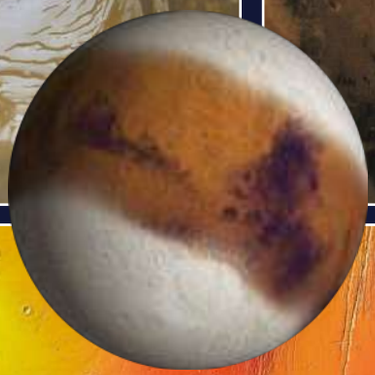
The edge of the king of super-volcanoes, Olympus Mons

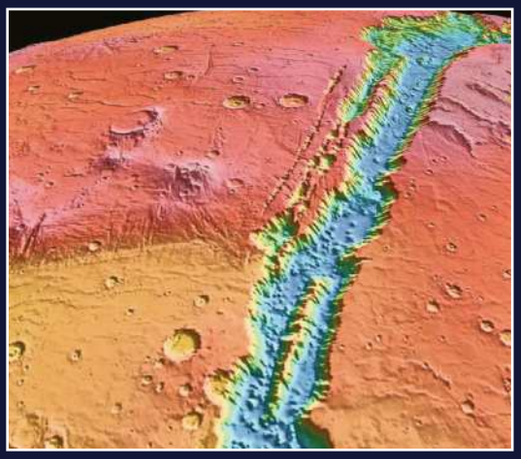
A giant sandstorm rages at 120km/h (75mph) across Mars' surface

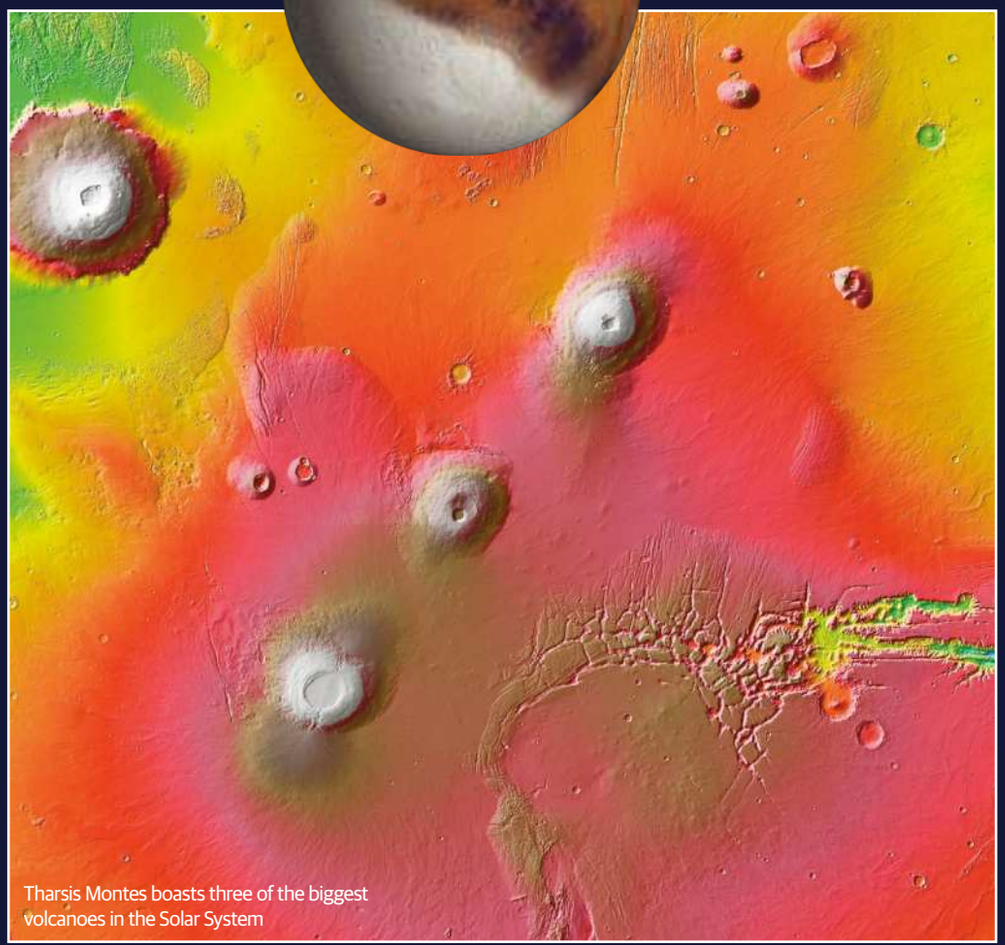


Valles Marineris is over 10km (6mi) deep in places

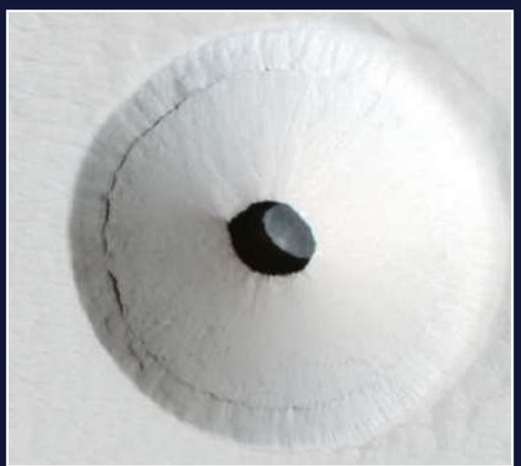
Ancient floods carved out the impressive Kasei Valles







Tharsis Montes boasts three of the biggest volcanoes in the Solar System



1 GRAND CANYON OF MARS

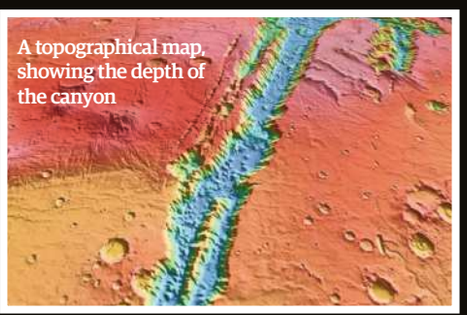
Welcome to Valles Marineris – the biggest canyon in the entire Solar System

It's difficult to recount exactly the impact the Grand Canyon has on you on your first visit. It's pretty overwhelming: at around 29 kilometres (18 miles) at its widest point and nearly two kilometres (1.2 miles) from the plateau to the Colorado River at its deepest, it's probably the biggest thing anyone could hope to witness in their lives. Yet the entire Grand Canyon would be no more than a mere gully in the biggest canyon in the Solar System.

Valles Marineris is unbelievably enormous, spanning over 4,000 kilometres (2,500 miles) in length, with some parts of it 200 kilometres (125 miles) wide and over ten kilometres (six miles) deep. It would stretch across the entire United States if it was on Earth and its size is only exaggerated by the fact that Mars is around half the size of Earth – around 20 per cent of Mars' circumference is taken up by this massive gouge in its surface.

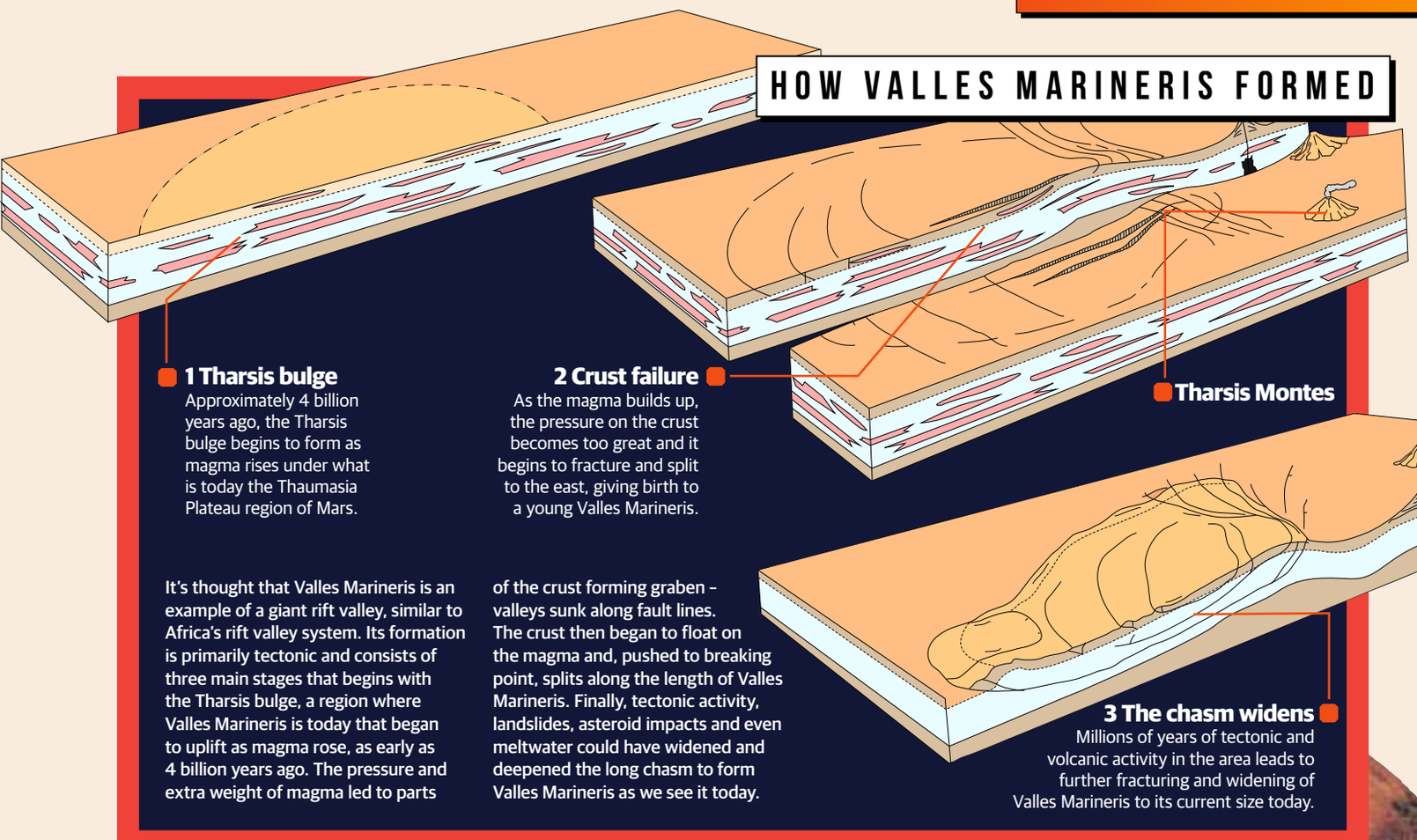
The canyon is, naturally, host to a plethora of interesting geological features that offer scientists clues as to its turbulent past. Located just south of Mars' equator, its western end begins with a series of steep, maze-like valleys given the sinister Latin title Noctis Labyrinthus, or 'the labyrinth of the night'. This region shows typical fault-line activity, with valley-forming depressions known as 'grabens'. Moving eastwards, Valles Marineris starts to grow in breadth and depth, with twin canyons called the Ius and Tithonium chasmata running parallel to each other, divided by a central ridge. This gives way to three more chasmata and the deepest part of the canyon at 11 kilometres (6.8 miles) from the plains above. These eventually lead to the eastern end: Coprates Chasma, defined by its layered deposits that could originate from landslides or water erosion, Eos and the Ganges chasmata and, finally, where the canyon terminates in the Chryse region, a mere kilometre (0.62 miles) above Valles Marineris' deepest point.

Although there's evidence of a number of processes at work here including water erosion, the scientific community generally agrees today that the volcanic region west of Valles Marineris played a major role in the formation of this huge rift, with water reshaping and deepening its course. It's thought that as the Tharsis Montes was pushed up by molten rock to form gigantic volcanoes, the crust split to form fault lines around 3.5 billion years ago, which inevitably widened to form Valles Marineris. Though they share many similarities, this is unlike the Grand Canyon on Earth, which was gradually carved out of the surrounding rock millions of years ago by the meandering of the Colorado River and its tributary streams.



A topographical map, showing the depth of the canyon

HOW VALLES MARINERIS FORMED



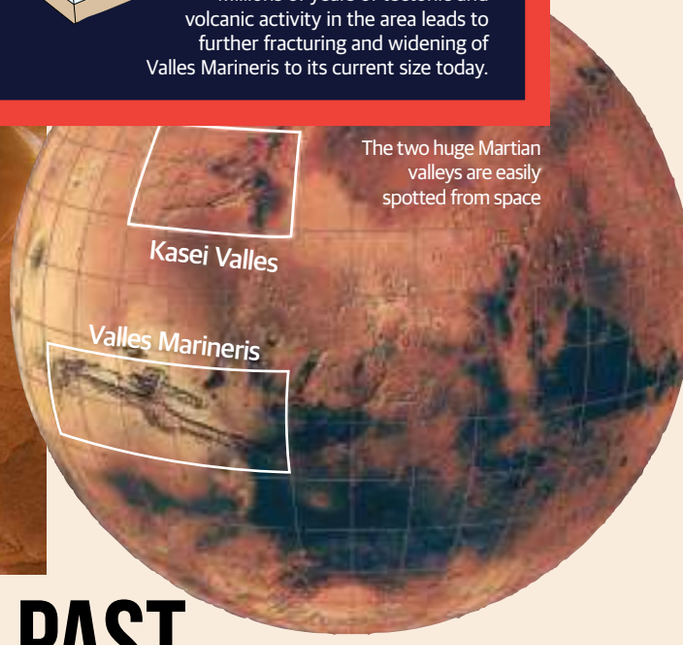
1 Tharsis bulge
Approximately 4 billion years ago, the Tharsis bulge begins to form as magma rises under what is today the Thaumasia Plateau region of Mars.

2 Crust failure
As the magma builds up, the pressure on the crust becomes too great and it begins to fracture and split to the east, giving birth to a young Valles Marineris.

3 The chasm widens
Millions of years of tectonic and volcanic activity in the area leads to further fracturing and widening of Valles Marineris to its current size today.

It's thought that Valles Marineris is an example of a giant rift valley, similar to Africa's rift valley system. Its formation is primarily tectonic and consists of three main stages that begins with the Tharsis bulge, a region where Valles Marineris is today that began to uplift as magma rose, as early as 4 billion years ago. The pressure and extra weight of magma led to parts of the crust forming graben – valleys sunk along fault lines. The crust then began to float on the magma and, pushed to breaking point, splits along the length of Valles Marineris. Finally, tectonic activity, landslides, asteroid impacts and even meltwater could have widened and deepened the long chasm to form Valles Marineris as we see it today.


This massive canyon was carved out by torrents of water



The two huge Martian valleys are easily spotted from space

2 CHASM WITH A VIOLENT PAST

Meet Valles Marineris' little brother

If it weren't for its bigger sibling several hundred kilometres to the south, Kasei Valles would have taken the gong for being the biggest canyon system on Mars, if not the Solar System. As it stands, its 3,000-kilometre (1,900-mile) expanse, three-kilometre (1.8-mile) depth is still more than prominent enough to stand out from the surface to any passing orbiter. It even tops Valles Marineris in places, reaching over 300 kilometres (185 miles) at its widest.

Its size isn't what makes Kasei Valles a wonder of Mars alone though. All 1.5 million square kilometres (nearly 600,000 square miles) of the region were forged by some of the most violent events in Mars' history. Today, the most potent force Kasei Valles faces is the occasional, turbulent dust storm that, given the thin Martian atmosphere, is hardly about to carve another record-breaking canyon into it. It was a different story over 3 billion years ago, though: the same raging tectonics that were busy creating Valles Marineris were ripping the landscape apart, bringing groundwater to the surface which combined with ice to create furious torrents of mud, forming and shaping the channels of Kasei Valles. The same violent floods failed to completely erode the outcrop of Sacra Mensa but further downstream, they made mincemeat of the Sharonov crater.

"THE REGION WAS FORGED BY SOME OF THE MOST VIOLENT EVENTS IN MARS' HISTORY"

3 SUPER VOLCANO

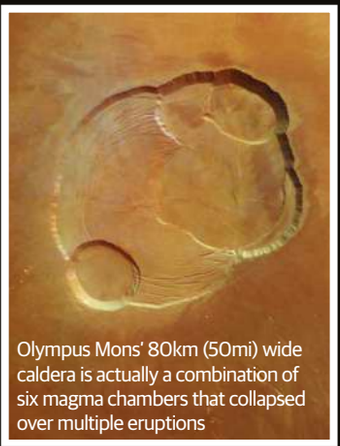
The tallest peak on Mars and in the Solar System

At some point in the distant future, when commercial space flights have reached the border of the asteroid belt and we can freely explore other planets, Olympus Mons will likely become the number one tourist destination in the Solar System, outside of any wonder on Earth. It holds some impressive titles, including the tallest known peak in the Solar System at 22 kilometres (14 miles) from base to tip and a diameter of around 624 kilometres (374 miles), nearly the same size as France and about the same size as the US state of Arizona. It has a caldera to match its enormous expanse: at around 80 kilometres (50 miles) in diameter, these six collapsed magma chambers form a single crater-like depression that's easily large enough to comfortably hold one of the biggest cities in the world by area, New York, with plenty of room to spare. And the volume of Olympus Mons is equally huge at around 100 times that of the Hawaiian volcano Mauna Loa, which is enough to contain the entire Hawaiian archipelago from Hawaii to Kauai, in fact.

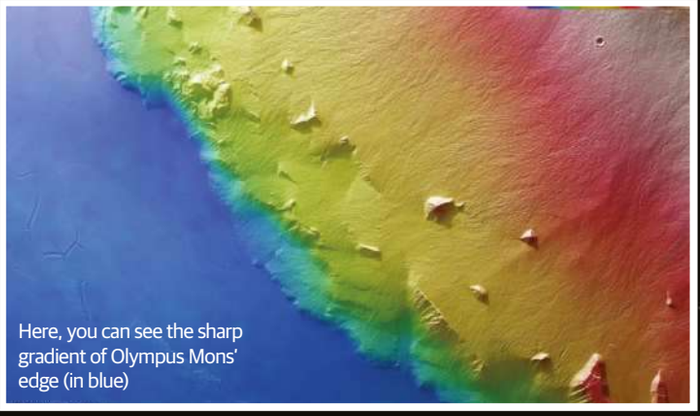
This is no mere mountain, however. Olympus Mons is a giant volcano, a shield volcano to be precise, the kind that spews lava slowly down its slopes rather than violently erupting magma, smoke and ash kilometres into the sky. As a shield volcano it has a low profile and its sides slope at an average incline of only five per cent. In fact, if you were standing at the top of Olympus Mons and didn't know it, you probably wouldn't be aware that you were at the summit of a very high mountain. If you walked to the far edge where the volcano begins to rise, you'd encounter an escarpment, or boundary cliff, an astonishing ten kilometres (six miles) high. That's higher than the largest volcano on Earth, Hawaii's own shield volcano Mauna Loa.

Olympus Mons towers far above the biggest mountain on Earth

Olympus Mons' giant size is no fluke. Low Martian gravity has a part to play in the continuous build-up of cooling lava on its flanks. But tectonic activity on Mars is extremely limited compared to Earth, too: unlike the Hawaiian islands, for example, which have produced several smaller volcanoes as a result of plate movement over millions of years, Olympus Mons has been sitting in the same spot for a long time, allowing the volcano to continuously erupt and grow to its current size.



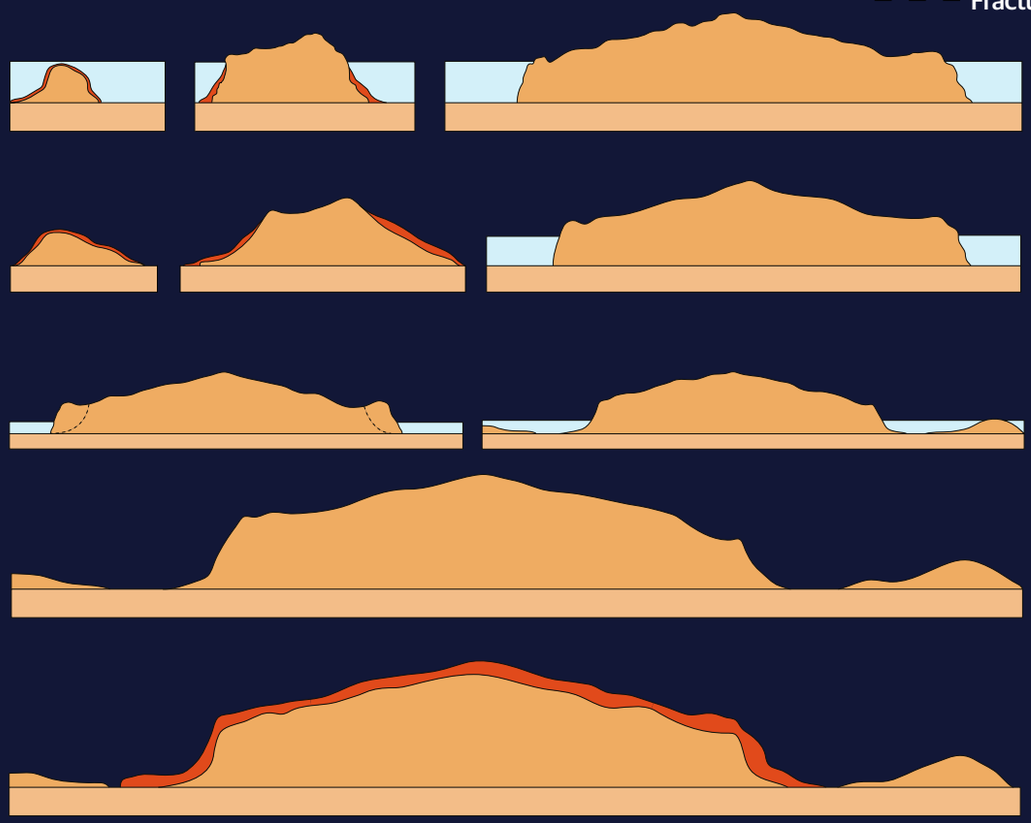
Olympus Mons' 80km (50mi) wide caldera is actually a combination of six magma chambers that collapsed over multiple eruptions



Here, you can see the sharp gradient of Olympus Mons' edge (in blue)

HOW OLYMPUS MONS WAS CREATED

The theories on how the biggest volcano in the Solar System formed



SUBAQUA BIRTH
One theory is that lava flowed underwater, piling up until it reached the surface and then spread out sideways after.

SUBAERIAL BIRTH
In the subaerial theory, the lava piled up and flowed in the air, with water rising later to change the dynamics of the lava flow.

LANDSLIDES
Regardless of whether Olympus Mons was partially underwater or not, instability resulted in multiple landslides, reducing its size.

WATER DRAINS
As the water drained from the northern lowlands, further landslides shaped Olympus Mons, giving it its distinctive lopsided aureole.

NEW LAVA
When the water surrounding Olympus Mons disappeared, fresh lava flow smoothed its previously scarred surface.

4 VOLCANIC HOT SPOT

Tharsis Montes is responsible for Mars' most famous features

Mariner 9 was the first spacecraft to orbit another planet when it arrived at Mars in November 1971, with the Red Planet engulfed by one of its characteristic dust storms at the time. As the orbiter began to return unprecedented close-ups of the surface of Mars to Earth, NASA could make out three faint but distinctive spots. This was the Tharsis Montes region of Mars and the spots were actually the peaks of three enormous volcanoes, evenly spaced in a northeast-southwest orientation. To the northwest, what had been known as 'Nix Olympica' since the 19th century and was suspected to be a mountain, was discovered to be a massive volcano, and it was subsequently renamed as Olympus Mons after Mariner 9 observed it.

From north to south, the volcanoes are Ascraeus Mons, Pavonis Mons and Arsia Mons

Tharsis Montes is the biggest volcanic region on Mars: it's some 4,000 kilometres (2,500 miles) wide and is home to 12 huge volcanoes up to 100 times bigger than their equivalent on Earth.

The Tharsis Montes region is responsible for many of Mars' more interesting wonders. Around 4 billion years ago, rising magma caused what is now a plateau to rise, forming the Tharsis bulge, a geological feature the size of North America. This led to the formation of Valles Marineris, the Tharsis Montes volcanoes and Alba Mons, a huge volcano with a diameter of roughly 1,500 kilometres (930 miles) but with an extremely low relief that makes it unique on Mars. Olympus Mons is often (understandably) attributed to the area, although it's actually not part of the plateau.

5 MARTIAN TWO-FACE

The planet-shattering reason behind Mars' strange north-south divide

Sometimes it's hard to see the woods for all the trees, as is the case with the strange, near-hemispheric dichotomy of Mars' southern highlands and northern lowlands. The difference between the two hemispheres has been observed for decades now, with investigation by orbiting probes in the late Seventies highlighting the radical contrast between the topography of each region: the south is rugged, volcanic and pock-marked with craters and features the tallest peaks in the Solar System, while the north is a huge plain of unparalleled smoothness, with an altitude typically several kilometres below the lower regions of the south. Up until recently no one really knew why this was, although it was known that this feature was very ancient, almost as old as the planet itself.

A few theories had been postulated as to why the two halves were so different: one was that convection in the mantle caused upwelling in the south and downwelling in the north. The other, originally proposed in 1984, was that the hemispheric dichotomy was the result of a single enormous impact. It was the simplest solution to the mystery that meant the entire northern region, an area 8,500 kilometres (5,300 miles) wide and 10,600 kilometres (6,600 miles) long, was a colossal impact basin. However, that theory quickly got shot down because the borders of the northern hemisphere didn't fit the expected round shape of an impact crater.

However, since the Eighties, several confirmed craters have been discovered with strangely elliptical borders, such as the Moon's South Pole-Aitken basin. The case for the massive impact theory wasn't helped by the fact that the Tharsis bulge and its enormous volcanoes formed after this huge crater was created, obscuring the shape of the rim on one side. So it was only after two decades of surface and gravitational field observations by various spacecraft that the unambiguously elliptical impact basin of the northern hemisphere was revealed.

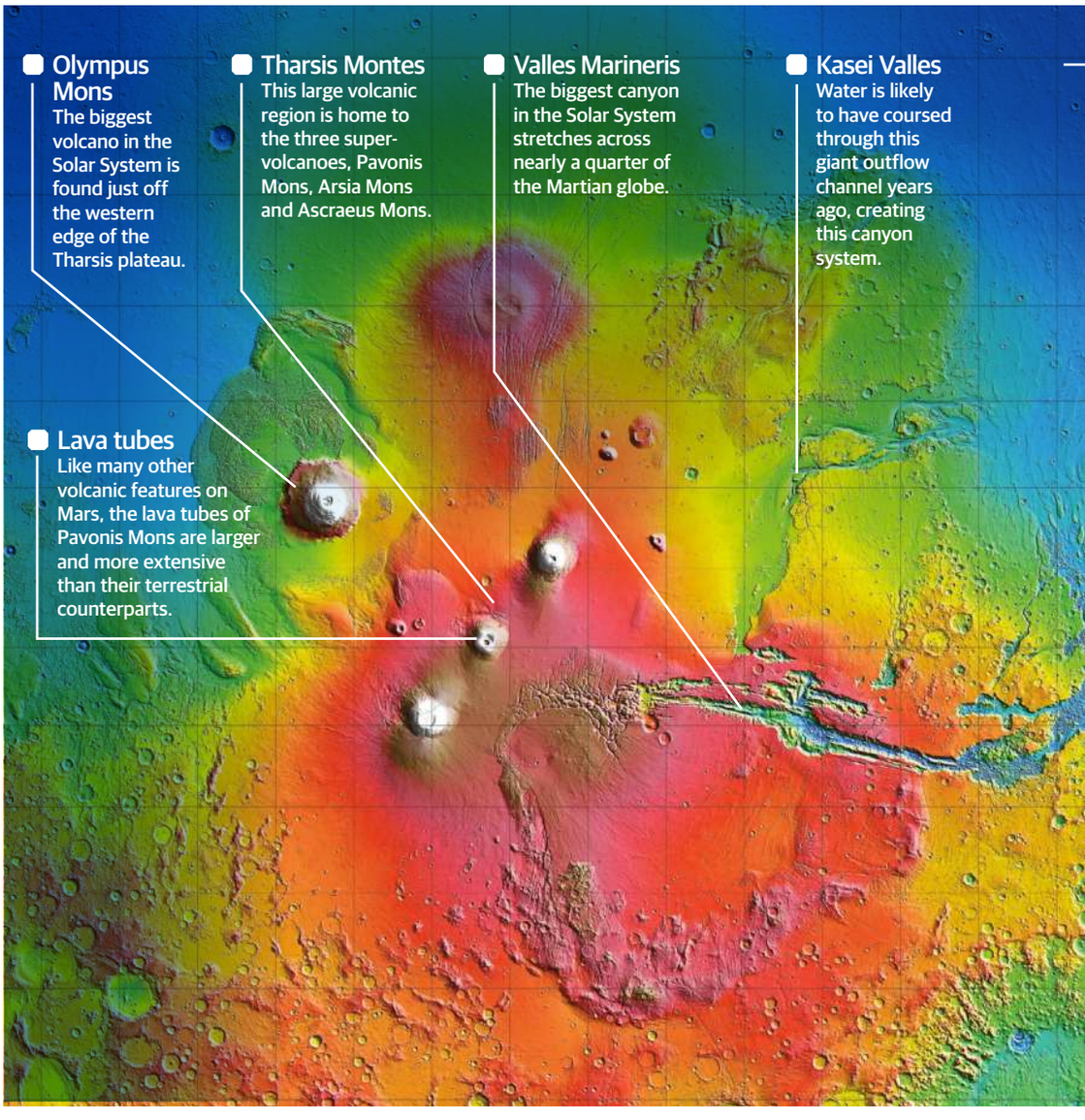
Today, although the giant impact theory hasn't been proved beyond doubt, the evidence weighs heavily in its favour. The Borealis Basin, if it is the result of an ancient impact, will be the largest known crater in the Solar System: covering an area of around 90 million square kilometres (35 million square miles), it's larger than the continents of Europe, Australia and

MAPPING THE SURFACE OF MARS

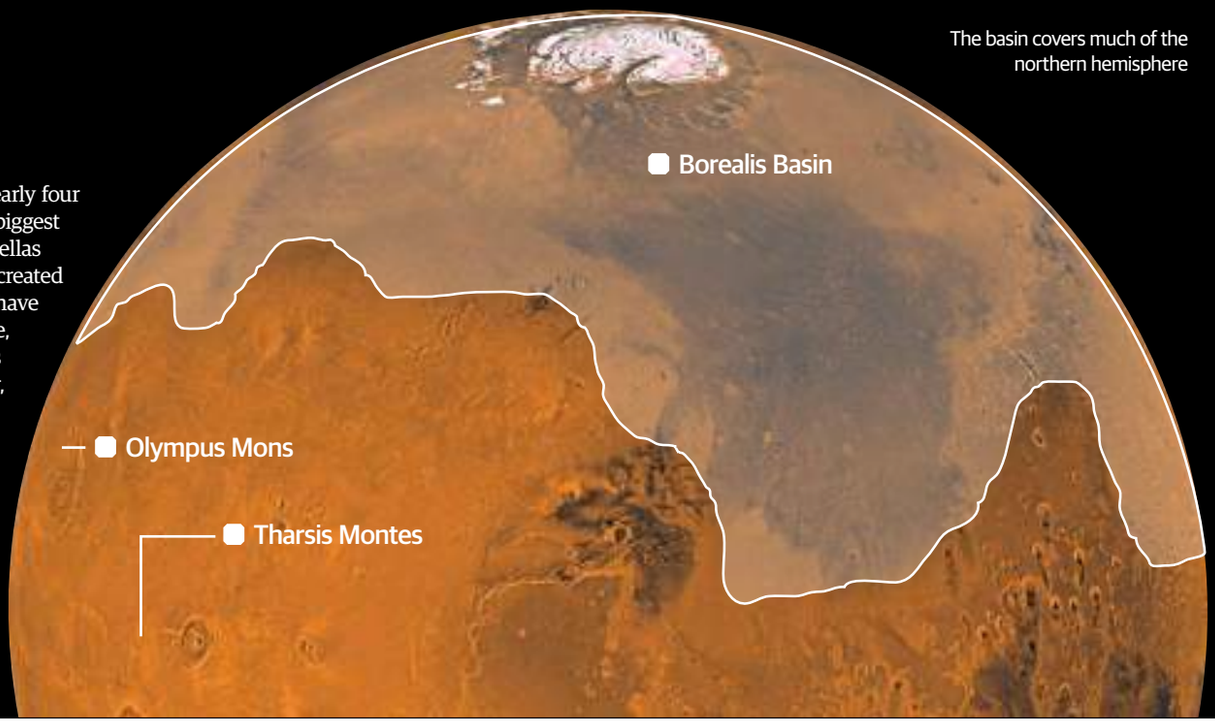
The Mars Global Surveyor was sent to orbit Mars with the expressed goal of doing the job of a terrestrial surveyor, but on an enormous scale. Among its major missions (which included surveying the Martian atmosphere and interior), it was tasked with mapping the entire Martian surface and geology with the aim of providing the foundations of future NASA missions for years to come.

Using the Mars Orbiter Laser Altimeter (MOLA) this mission was phenomenally successful, creating a flat, high-resolution map from over 640 million elevation measurements assembled into a global grid with an accuracy that ranged from 13 metres (42 feet) to within two metres (six feet). The map is so accurate and complete that it gives us a better knowledge of Martian topography than some continental areas of Earth.

The findings of this survey include the discovery of Mars' full topographic range, which is about one and a half times that of Earth and goes from the deepest trough in the Hellas Impact Crater to 30 kilometres (19 miles) higher at the tallest point of Olympus Mons. The Mars Global Surveyor also gave us a much clearer idea of the dynamics of water on the surface of the Red Planet, with the huge difference in elevation between the northern and southern hemispheres meaning that the lowlands of the north would have drained around three-quarters of the surface of Mars, at an earlier period in Martian history when water could have flowed freely on the surface.

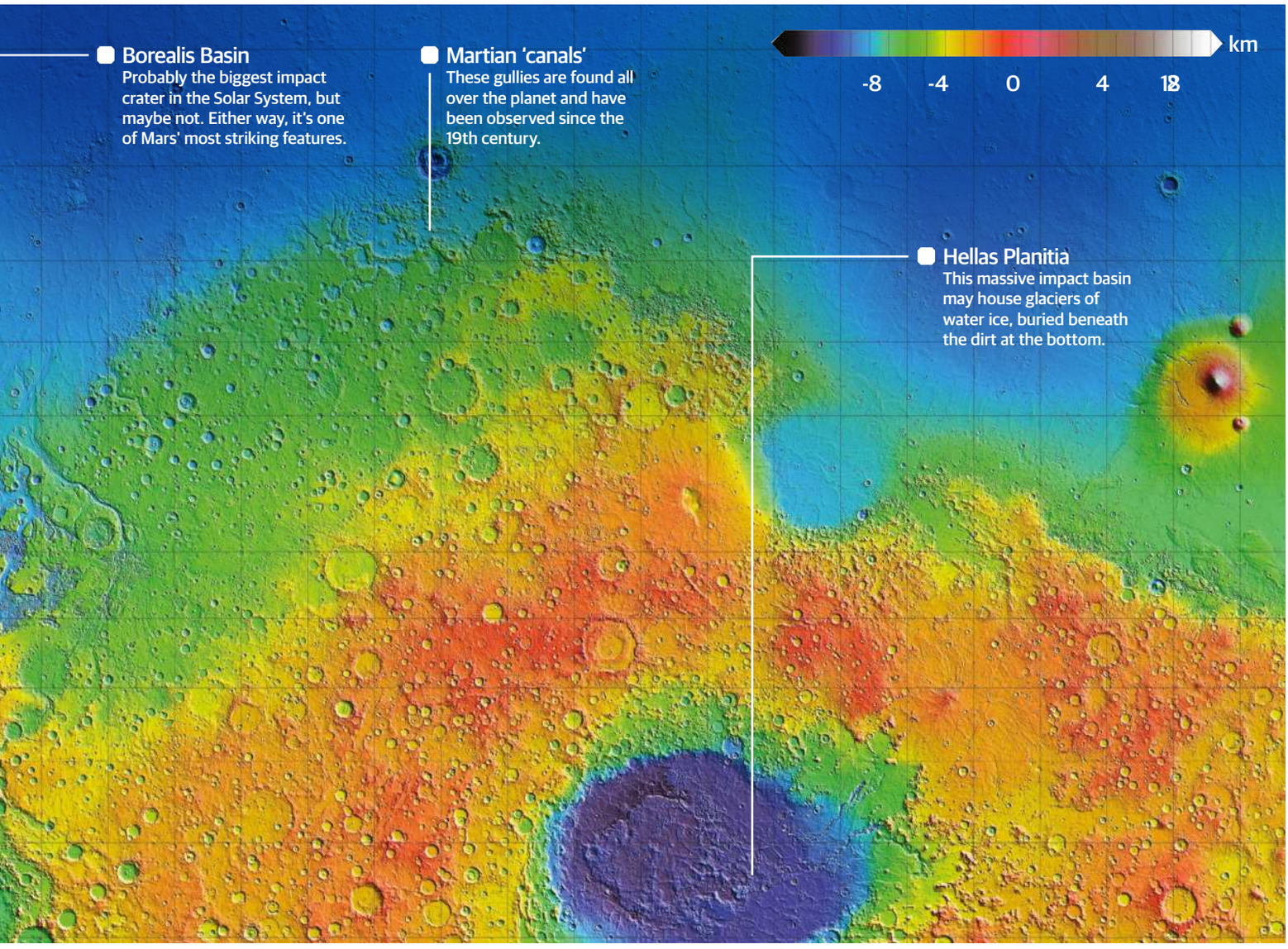


10 WONDERS OF MARS



The basin covers much of the northern hemisphere

Asia combined. That's nearly four times as big as the next biggest known crater on Mars, Hellas Planitia. The object that created the Borealis Basin must have been terrifyingly massive, around 2,000 kilometres (1,200 miles) in diameter, striking at an angle of 45 degrees to create the elliptical basin. These objects and collisions were relatively common 4 billion years ago, shaping the geography and the orbits of the planets to mould the Solar System.



Borealis Basin
Probably the biggest impact crater in the Solar System, but maybe not. Either way, it's one of Mars' most striking features.

Martian 'canals'
These gullies are found all over the planet and have been observed since the 19th century.

Hellas Planitia
This massive impact basin may house glaciers of water ice, buried beneath the dirt at the bottom.

6 GIANT DUST STORMS

The enormous clouds of fine red dust that can sometimes grow to engulf the entire planet

The surface of Mars is covered in dust far finer than the sands of any desert on Earth – indeed it's the iron oxide (rust) content of this dust and the underlying rock that gives the planet its distinctive ruddy colour. From month to month, the gentle Martian winds blow clouds of dust across the landscape, stripping the surface sands away to reveal underlying rock in some places, and accumulating in other places to form spectacular dunes.

Normally, these billowing dust storms flare up and die away in a couple of days, but occasionally they can grow in size to the scale of entire continents before subsiding. And every couple of years, around the time of Mars' closest approach to the Sun, they can run out of control to wrap the entire planet in an orange murk that persists for several months.

These enormous storms are only possible because of the size of Martian sand – the Red Planet's thin atmosphere (exerting just one per cent of the Earth's atmospheric pressure) means that even the strongest winds of around 120 kilometres per hour or 75 miles per hour (equivalent to hurricane force on Earth), would barely be able to shift Earth-sized sand grains. But atmospheric dust grains on Mars, worn down by billions of years of steady erosion, are comparable in size to the particles in cigarette smoke, so that even the gentle winds of the planet's thin atmosphere can lift them from the ground. Wind speeds in a typical storm are around 100 kilometres per hour (62 miles per hour), but an astronaut on the surface would barely feel that as a light breeze.

Once lofted into the air, dust particles may linger for months. The reasons for this persistence are still uncertain, but it's possible that weak electromagnetic fields help to repel them from each other and prevent them settling back on the ground. This means that once the dust particles are stirred up, they can move at speeds many times faster than those in dust storms on Earth, and travel much further. As they absorb sunlight and prevent it from reaching the surface, atmospheric temperatures may rise dramatically by up to 30 degrees Celsius (86 degrees Fahrenheit).

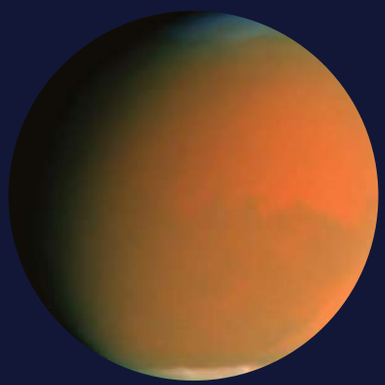
Awesome though they may appear, the main threat from storms to either current Mars rovers and landers, or future astronauts, comes from the dust they carry within them. As it settles back out of the atmosphere it may coat equipment and solar panels with particles that get into delicate mechanisms and cut down the efficiency of solar panels. Fortunately, NASA engineers have discovered that encounters with the occasional 'dust devils' that spiral across the Martian surface can also help remove dust and restore power.

"DUST STORMS CAN WRAP THE ENTIRE PLANET IN AN ORANGE MURK FOR SEVERAL MONTHS"

The air is so thin on Mars, an astronaut would barely be able to feel this raging storm

STORM CYCLES

In June 2001, the Hubble Space Telescope captured this crystal-clear image of Mars, highlighting clouds around its north and south poles



Three months later, as Mars approached perihelion, a planet-wide dust storm blocked Hubble's view of everything but the bright polar caps

Major dust storms are typically most common around Martian perihelion (the planet's closest approach to the Sun). Because the orbit of Mars, unlike that of the Earth, is distinctly elliptical, it receives up to 40 per cent more sunlight around this time, which helps to create strong temperature differences across the planet that in turn generate high winds. Unfortunately for earthbound astronomers, perihelion is also the best time to view Mars, so the Red Planet is frequently engulfed in clouds around the time when it is at its largest and brightest in Earth's skies. Even space probes are not immune to the problem – in fact Mariner 9, the first space mission to enter orbit around Mars, arrived during a major dust storm in November 1971 and had to wait for about a month until the atmosphere cleared and it was able to send back the first detailed photographs of the Martian surface.

7 SUBTERRANEAN LAVA TUBES

A hidden world of caves that could shelter Martian microbes

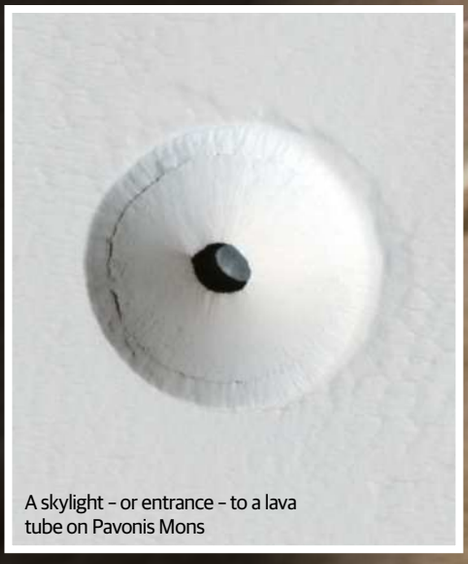
Rising to about 12 kilometres (7.5 miles) above the surrounding dusty plains, Pavonis Mons is roughly three kilometres (1.9 miles) higher than Everest. However, it has another feature that qualifies as a Martian wonder in its own right.

Running down the volcano's southwest flank are a number of parallel, tadpole-shaped features that look at first like empty riverbeds. Tens of kilometres long, their heads point roughly towards the volcano's summit, while their tails peter out or merge to form broader depressions in the landscape.

But these valleys are not the work of water erosion. Known as 'lava tubes', they form when the surface of a lava flow starts to cool and solidify, but molten rock continues to run below the surface. When the eruption finally comes to an end, the underground river of lava may drain away completely, leaving behind a cavernous subterranean passage.

Normally, lava tubes are all but invisible from the surface, but over time, the weight of overlying rock may cause their ceilings to cave in, creating steep-sided valleys like the ones seen on Pavonis Mons. In other places, the surface may just subside to form a string of circular depressions known as a pit chain. When the middle of the depression then collapses inward, the result is a 'skylight' opening into the lava tube.

When the first astronauts reach Mars, they may head straight for these curious portals. Lava tubes offer natural protection from the harsh surface environment, and are an obvious place to set up a long-term base. And for the same reasons, they are also one of the most promising places to look for simple Martian life.



A skylight – or entrance – to a lava tube on Pavonis Mons

This perspective view of Pavonis Mons from ESA's Mars Express Orbiter reveals circular pits dotted among the longer, fully collapsed lava tubes

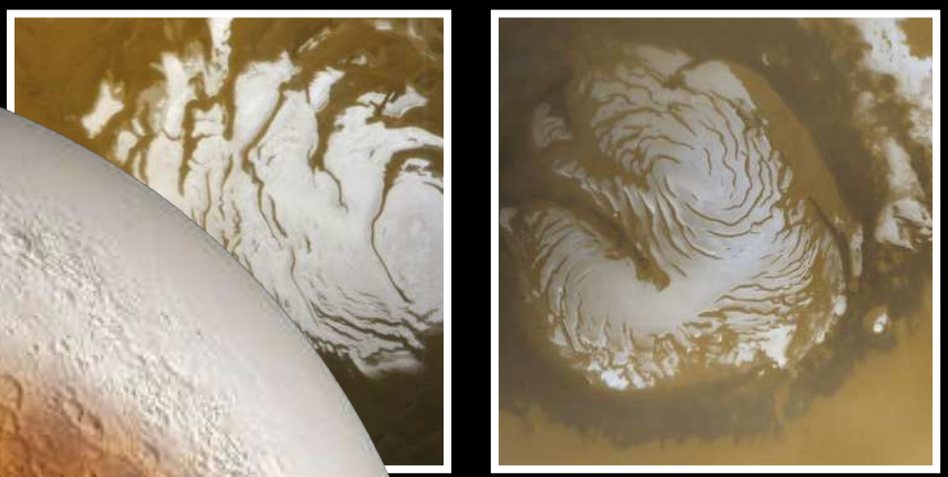
8 FROZEN CARBON DIOXIDE POLES

Mars has two permanent ice caps, but they're not like Earth's poles...

The temperature at the Martian equator is probably not as bitter as you might think, pushing the mercury as high as 20 degrees Celsius (68 degrees Fahrenheit) during the Martian summer, with a soil temperature that has been recorded close to a positively beachy 30 degrees Celsius (86 degrees Fahrenheit). It's a different story at the planet's much colder poles, however: with a desperately thin atmospheric pressure of just 600 pascals to insulate them – a fraction of Earth's 101,000 pascals – very little heat is retained at either end of the Red Planet. Here, the temperatures have been known to drop to as low as a bitterly cold -153 degrees Celsius (-243 degrees Fahrenheit) in the complete darkness of a Martian polar winter.

The Martian caps are pretty puny compared to those on Earth. The biggest of the two, the northern ice cap, has an estimated volume of 1.6 million cubic metres (56 million cubic feet), while the Antarctic ice sheet, the biggest on Earth, has a volume of 26.5 million cubic metres (935 million cubic feet). However, the extreme cold at the Martian poles results in over a quarter of Mars' atmosphere freezing into enormous slabs – and because over 95 per cent of Martian air is carbon dioxide, winter brings a deposit of up to two metres (6.5 feet) of dry ice. When summer comes around, rising temperatures cause the frozen carbon dioxide to sublimate (turn immediately from solid to gas) and return to the atmosphere. The changes in the amount of carbon dioxide in the atmosphere, along with the increasing and receding poles during summer and winter, is so great that the gravitational field of Mars changes with the seasons as a result.

Mars also experiences ice ages across hundreds of thousands of years, caused by marginal changes in its orbit and axial tilt. Like Earth it's currently in an interglacial period, but from around 2.1 million to 400,000 years ago, a time when sabre-toothed cats, woolly mammoths and other Pleistocene megafauna roamed Earth, Mars was plunged into an ice age of its own. The tilt on its axis heated the poles, evaporating ice into the atmosphere only for it to settle and spread from the 60 degree latitude mark to around 30 degrees north of the equator in both hemispheres.



The Martian north pole (right-hand image) can get even colder than the south (left) in a Martian winter, and reaches temperatures as low as -153°C (-243°F)

Mars during its ice age over 400,000 years ago. The ice caps reached the equivalent latitudes of Mexico in the north and Australia in the south

The Martian polar caps are shown in this Hubble image of the Red Planet taken in 2001. A huge dust storm can also be seen at the northern cap

9 DEEP IMPACT

The huge Martian crater that's visible from Earth

Hellas Planitia is a huge crater that was formed in the early days of the Solar System, an era of heavy meteorite bombardment around 4 billion years ago when enormous objects flew around and collided with others on a regular basis. With its bright, reflective floor it's a spectacular site, even when viewed from Earth.

It has a diameter of 2,250 kilometres (1,400 miles) and over nine kilometres (5.6 miles) separate the rim of the crater from its floor. The rims are nearly two kilometres (1.2 miles) high, which puts the floor of the basin seven kilometres (4.3 miles) below what on Mars would correspond with sea-level on Earth. At this depth, the atmospheric pressure at the bottom is nearly double that at the top. Under certain conditions, that's enough for liquid water to form. There's evidence to suggest that the gullies around the basin rim were formed by glacial movement as well as explosive boiling of the water into steam.

Hellas Planitia would be the biggest crater on Mars, if it wasn't for the suspected (but still unconfirmed) Borealis Basin in Mars' northern hemisphere.

This massive impact basin can easily be seen from Earth

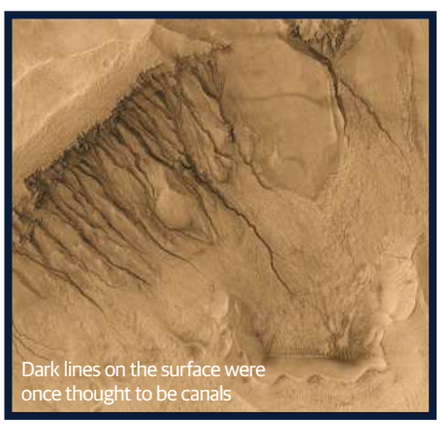
10 MARTIAN 'CANALS'

The features that went on to inspire a century of science fiction

In 1877, astronomer Giovanni Schiaparelli observed numerous gullies criss-crossing the surface of Mars, which he described in his native Italian tongue as 'canali'. For better or for worse, the literal translation of 'canals' was made into English and from there, early 20th century academics (including Percival Lowell, who popularised the idea), flushed with the prominence of a new scientific age, promptly assumed that evidence of an intelligent civilisation could be inferred from what seemed to be manufactured waterways.

Fortunately, others were more scientific in their observations, pointing out that the 'canals' were caused by an optical illusion in poor-quality telescopes that joined visible features by lines. Spectroscopic analysis showed that atmospheric pressure on Mars was indeed too low for liquid water and that the Red Planet was considerably colder than originally anticipated. Finally, powerful telescopes of the day showed no such lines on Mars, which led to this rather tenuous theory quickly being debunked, although the notion of a Martian civilisation lived on in science fiction for decades.

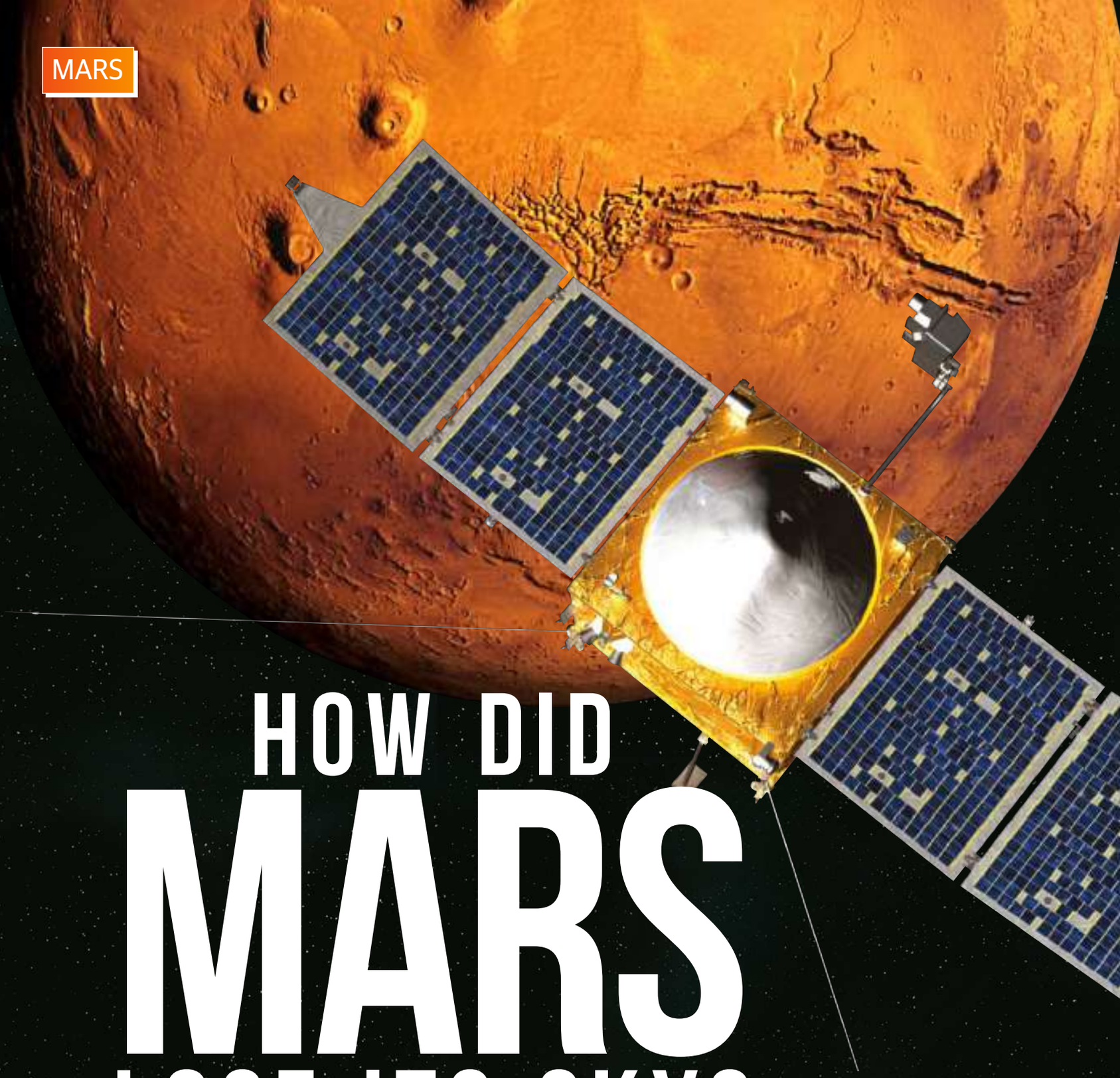
Today, albedo features – the craters and basins like Hellas Planitia that contrast with the russet background, as well as dust streaks and dust storms – can be considered the remains of what were once thought to be the great Martian canal system.



Dark lines on the surface were once thought to be canals

ARE WE MARTIANS?

The theory of panspermia, that an asteroid bearing the 'seeds' of life impacted the Earth aeons ago, isn't a new one. But following a major scientific conference in Italy recently, the idea that life on Earth may have originated from Mars, is picking up some serious traction. We don't know exactly how the building blocks of life came about, the RNA, DNA and amino acids that were brought together to form the prebiotic 'soup', but we're pretty sure that RNA was there first. On Earth, the minerals necessary for creating the RNA template would likely have dissolved in the oceans, but that wouldn't have been the case in the relatively arid environment of ancient Mars. The theory, outlined by Professor Steven Benner of the Westheimer Institute for Science and Technology, is that these minerals oxidised on Mars, eventually forming RNA. This was then transported to Earth and deposited via one or possibly many meteorites (Martian meteorite strikes are still very common today), conceiving the first life on Earth.



HOW DID MARS LOSE ITS SKY?

BILLIONS OF YEARS AGO, MARS HAD A THICK ATMOSPHERE. SO WHAT HAPPENED TO IT? THE MAVEN MISSION'S TOP BRASS EXPLAINS HOW THEY FOUND OUT WHERE IT WENT AND WHY

Words Ben Biggs

HOW DID MARS LOSE ITS SKY?

The core structure of the MAVEN spacecraft under inspection by technicians at Lockheed Martin in 2011

Today, Mars is a very cold, very dry planet with an atmosphere 100 times thinner than Earth, composed mostly of carbon dioxide. It has some weather, with clouds and winds that speed across the surface, picking up tiny dust particles that quickly bloom into enormous dust storms. It even snows sometimes, as small crystals of frozen carbon dioxide precipitate out of the sky. But it's a barren planet devoid of any environment that could support life, and it's been like this for billions of years. However, this hasn't always been the case.

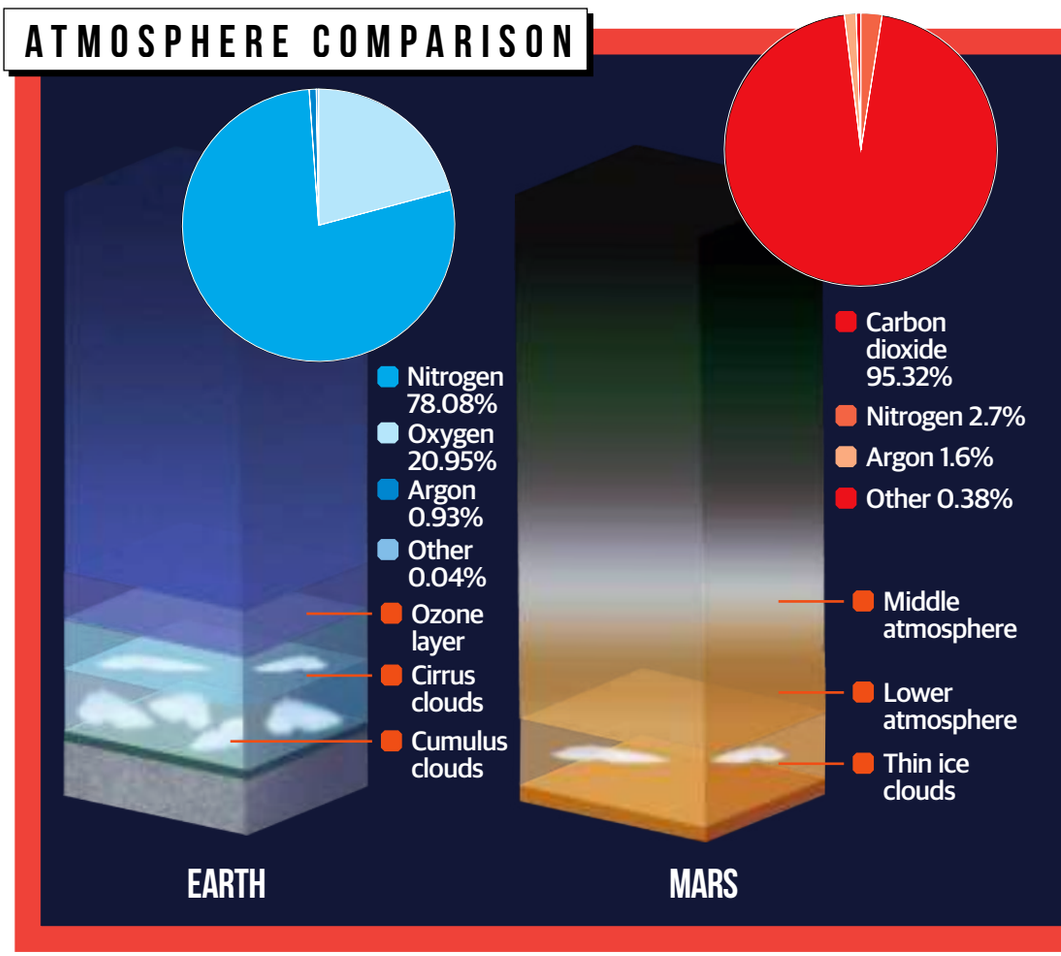
There are a number of theories that support the case for Mars once having a suitable environment for life to form, regardless of whether it did or not. Not least of all, there's the panspermia theory that Earth was seeded with the components of life by a meteorite of Martian origin. NASA's Mars Science Laboratory mission has also discovered tangible evidence for an ancient Martian environment, with liquid water flowing on its surface and a thick atmosphere. From the surface of the Red Planet, its Curiosity rover has measured the composition of Martian air as well as pieces of Martian rock that have elements of Mars' ancient atmosphere bound up in them, giving scientists a snapshot of what Mars was like several billion years ago.

That's only half of the story, though. To get a bigger picture of what Mars was really like, NASA recently launched the MAVEN (Mars Atmosphere and Volatile EvolutioN) spacecraft to Mars, to enter Martian orbit in September 2014 and become the first probe to explore the upper atmosphere of the Red Planet. "The reason MAVEN is going to Mars," project manager Guy Beutelschies tells us, "is that the other missions before it have found that there used to be liquid water on the surface: oceans, rivers, lakes... we can see the outlines of shore lines, found rocks on the surface that only form in the presence of water. So we know there was water on the ground once, but the atmosphere's too thin to support water on the surface – it would immediately evaporate," he continues.

"The observations that drive our thinking," MAVEN's principal investigator Bruce Jakosky clarifies, "are the presence of geological features that suggest the presence of liquid water on early Mars. Because Mars is farther from the Sun than Earth is and because we think that the Sun was dimmer early in history than it is today, there must have been a thicker atmosphere early in history to make temperatures warmer. Temperatures may have been more 'Earth-like' but the atmosphere probably was made up mostly of carbon dioxide – CO2. There may have been clouds, it may have rained or snowed and the sky may even have been blue like ours, but the atmosphere would not have been breathable by humans.

"The geological features that indicate that liquid water was present occur on the ancient

ATMOSPHERE COMPARISON




The MAVEN cone, complete with protective shield, that topped its Atlas V launch vehicle

surfaces, and then stop relatively suddenly. We think that the change from a warmer, wetter environment to the colder, drier one that we see today must have occurred over a period of maybe several hundred million years, and that the transition was essentially complete by around 3.5 billion years ago," he adds.

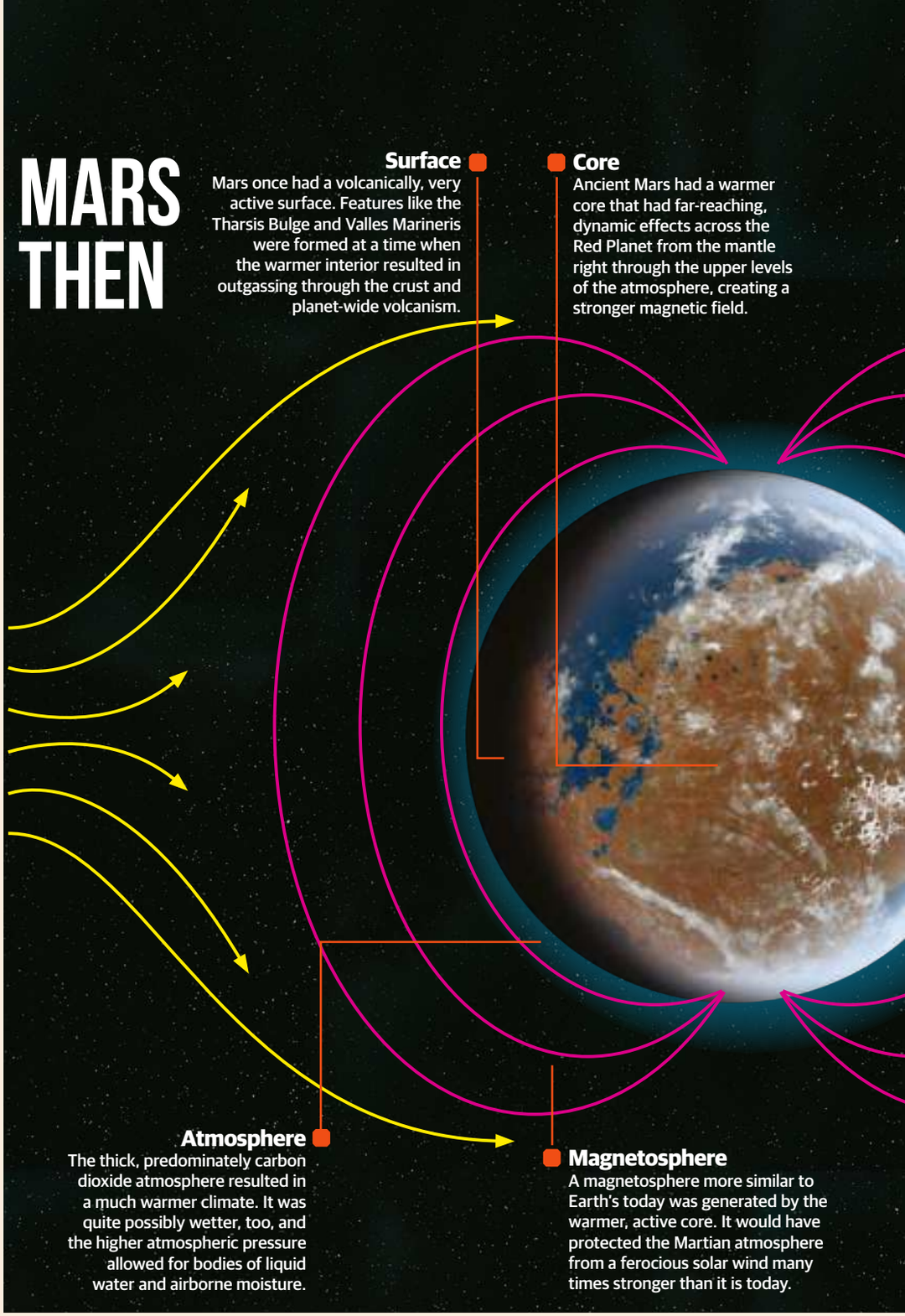
There's another mystery, the answer to which is perhaps even more interesting than the truth behind what Mars was really like aeons ago: what happened to its atmosphere? Was it swept off the planet in a cataclysmic event, or did it gradually seep away into space – and how did this happen?

Data from the Curiosity rover suggests that Mars hasn't changed very much in the last few billion years. However, for a relatively short time after its formation 4.5 billion years ago, Mars was host to rivers and liquid bodies of water that were neutral in pH and not too salty for the planet to become home for microbial life. Then, some time around 3.5 billion years ago, about the same time that simple-celled organisms were proliferating on Earth, Mars' atmosphere disappeared and subsequently, its liquid water evaporated or froze as the air pressure and mean temperature plummeted. Any life that might have existed at the time would have perished. "From a science point of view it's one of the biggest questions," Beutelschies explains. "We know there was water there but we don't know how long it was there for... so for people trying to figure out what the history of Mars was, especially if life was there, it's a pretty big and unanswered question right now. MAVEN being able to answer that question is going to help guide scientific investigation in the future."

At around the same time, the Solar System was still forming during a period known as the Late Heavy Bombardment. It was a dangerous time for all the young planets, as there were an enormous number of bolides flying around and impactors were far more frequent than they are today. According to some theories it's possible that one, or several of the great impacts evident on Mars could have created a shockwave that blasted the atmosphere off the planet and irrevocably changed the Red Planet's environment.

Some scientists believe that Mars' atmosphere never left the planet, and that most of the carbon dioxide that was once in the atmosphere became bound up in the rock of the planet. It was gradually trapped by a chemical reaction with the minerals common in Martian rock, resulting in liquid water being present on the surface as recent as 700 million years ago. That's not what MAVEN scientists believe, however. "Why do we think that the upper atmosphere was important for understanding this climate change?" poses Jakosky. "Two reasons: first, we see little or no evidence for a subsurface storage of the CO2 from an early thick atmosphere; there are no deposits of carbon-bearing minerals, for example, which are large enough to hold that much CO2. Second, there are measurements of isotopes in the Martian atmosphere that show enrichment of the heavier ones, a strong indication that escape to space has been an important process. If escape was important, then it occurred from the top of the atmosphere and would have involved interactions with the solar wind and other solar energetic drivers. With MAVEN, we're planning to study the top of the atmosphere and its interactions with the Sun in order to understand how escape occurs."

The theory that gained the most traction, one that the MAVEN scientists eventually proved, is that the atmosphere was very suddenly blown



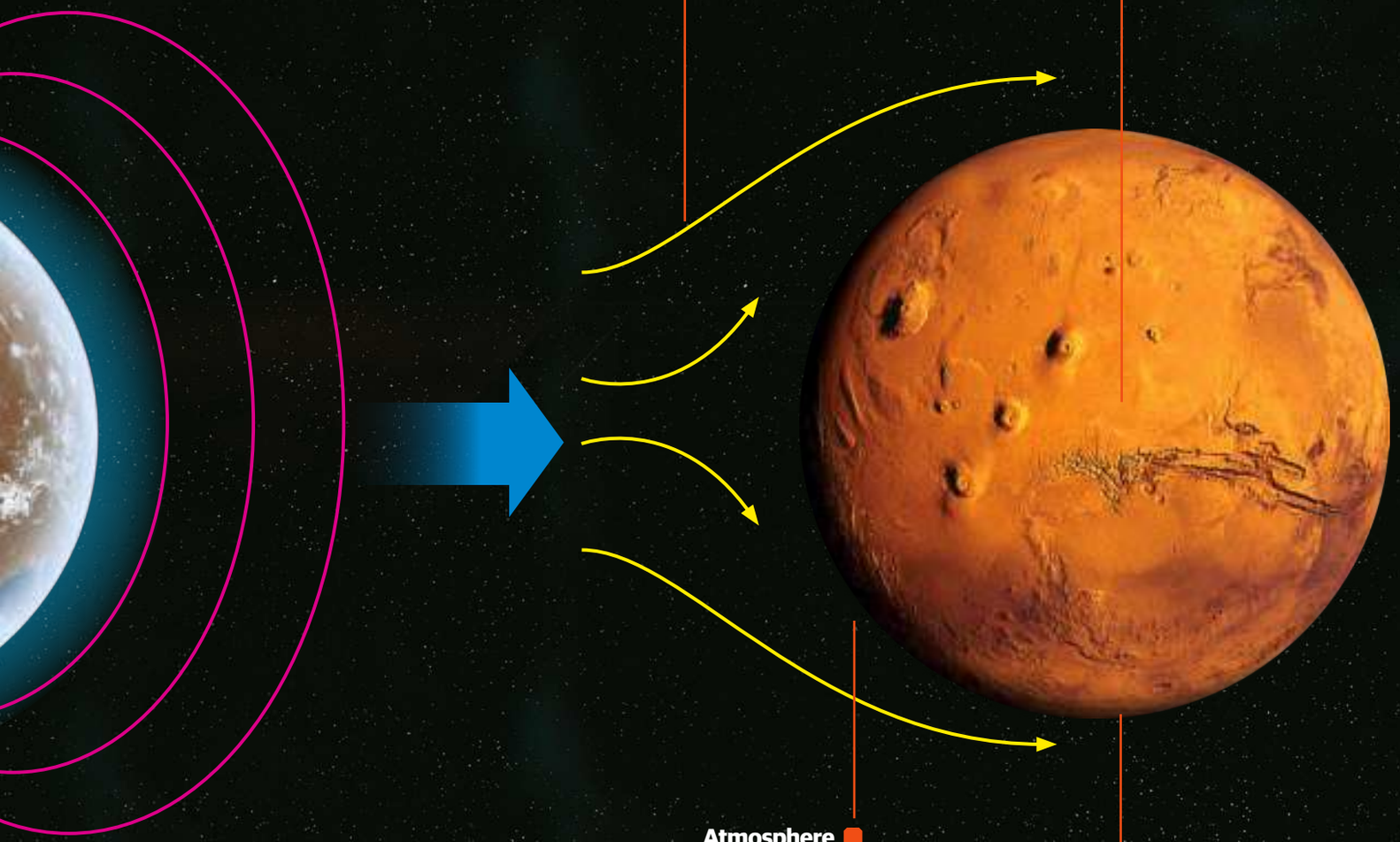
"IF ESCAPE WAS IMPORTANT, THEN IT OCCURRED FROM THE TOP OF THE ATMOSPHERE"

BRUCE JAKOSKY,MAVEN PRINCIPAL INVESTIGATOR

MARS NOW

Magnetosphere
A significantly weakened global magnetic field has led to the not-so-gradual erosion of Mars' atmosphere, most of which was stripped away 3.5 billion years ago.

Core
It's thought that for some reason, the Martian core cooled. Without any core convection, Mars' global magnetic field ebbed away to nothing.

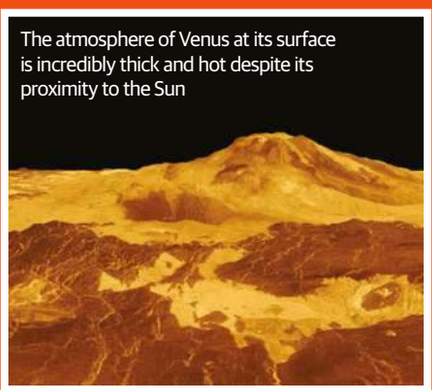


Atmosphere
Today, the thinner atmosphere has resulted in reduced greenhouse warming and much lower temperatures. Some of the remaining gases in Mars' thin atmosphere have either condensed or reacted with rock on the surface.

Surface
As a direct result of a colder core, tectonics ground to a near halt and volcanism on Mars became significantly less dynamic. Today, the surface is about as dead as it is red.

THE POWER OF SOLAR WINDS

On Earth, a strong magnetosphere deflects the solar wind around our planet because the charged particles flow along its magnetic field lines, reducing its effects to zero. With Mars' almost insignificant magnetic field, however, a powerful solar wind was able to penetrate the upper levels of the atmosphere billions of years ago. This gave the particles in the atmosphere enough energy to achieve escape velocity and leak into space, leaving Mars with a much thinner atmosphere today. Little or no magnetosphere doesn't necessarily mean a thin-atmosphere planet, though. Venus, for example, not only has a weak magnetic field compared to the Earth but it's much closer to the Sun than either Mars or Earth. Given Mars' depleted atmosphere, you might assume that Venus would be devoid of any atmosphere altogether, but it's actually many times thicker than Earth's atmosphere with dense clouds and intensely hot surface temperatures of more than 462 degrees Celsius (864 degrees Fahrenheit). While the solar wind is gradually stripping the gases in the upper Venusian atmosphere, its dynamic pressure reaches a balance with the extreme pressure of the thicker lower levels, preventing much of the effect of solar wind stripping.



The atmosphere of Venus at its surface is incredibly thick and hot despite its proximity to the Sun


MAVEN launched successfully from Cape Canaveral on 18 November

away by a strong wave of solar wind – the same thing that causes aurorae on Earth when it buffs up against our magnetosphere. The Curiosity rover has already shown that multiple isotopes of various elements, including carbon, nitrogen, oxygen and argon, exist in relatively high concentrations at all levels of the atmosphere – evidence that most of Mars' atmosphere has disappeared. It's thought that a sudden weakening in Mars' magnetic field resulted in its atmosphere being eroded by a fierce solar wind. "The core is important," Jakosky says, "because that is the source for creating a global magnetic field. And the presence of a magnetic field can keep the solar wind from hitting the atmosphere and stripping it off. When the magnetic field disappeared 4 billion years ago, that allowed solar wind to strip the planet's atmosphere."

The young Sun blasted Mars with 100 times the radiation it receives now and, with relatively little in the way of magnetosphere to repel the solar wave, Mars' atmosphere was eroded away relatively quickly. Some of what was left of the atmosphere then reacted with Martian rocks or condensed and froze on the surface.

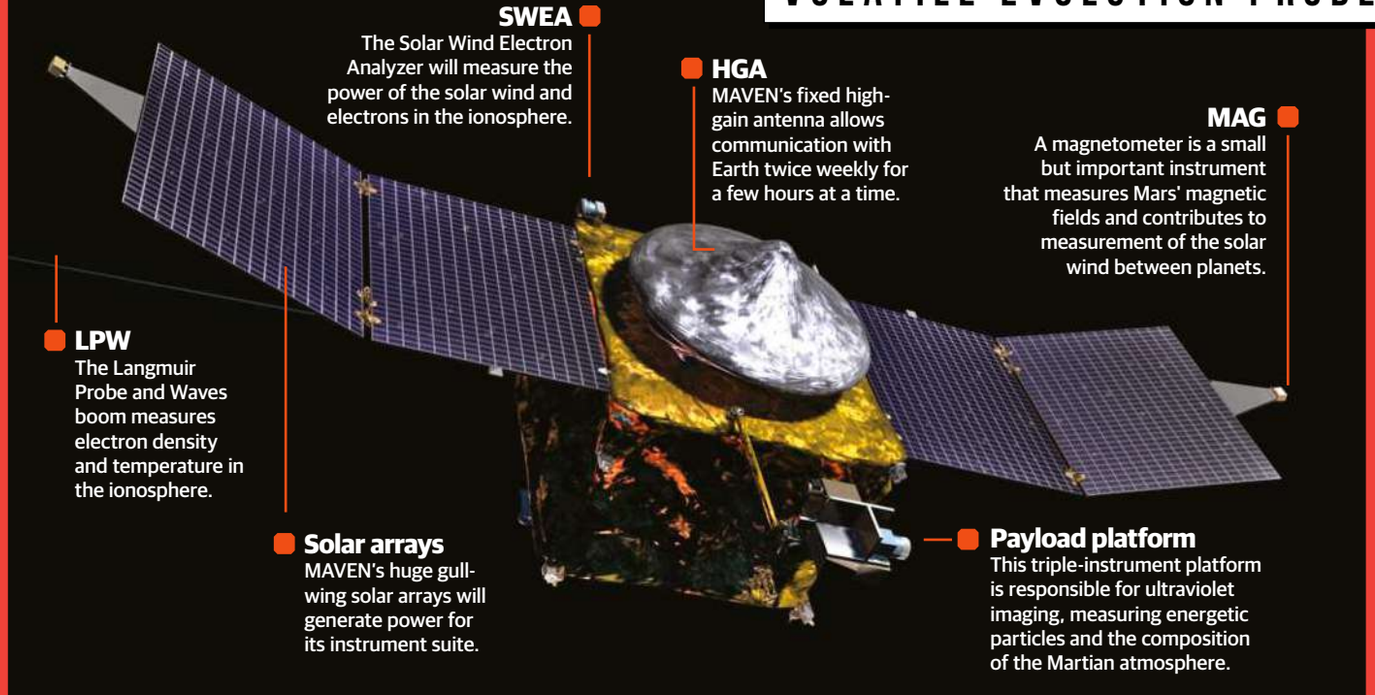
"This is one area where all [MAVEN's] instruments are playing together to try to answer the questions we're trying to solve," says Beutelschies. "We're looking at different aspects to try to understand the interaction of the solar wind with the atmosphere. What we're hoping to do is once we've taken this data, we can make an atmosphere model of Mars and use these models to go back in time. We can then see when the atmosphere would have been thick enough to support oceans and rivers and lakes on the surface of Mars, then know how long this water would have existed. Because if it's a long time, it has ramifications for people interested in answering the question of whether life could have evolved on the Red Planet."

The Mars Science Laboratory mission, if anything, raised as many questions as it has provided answers, giving MAVEN a challenging job on its year-long primary mission. But the timing of the spacecraft's launch to more or less coincide with the solar maximum was quite deliberate. With the peak of the solar cycle, the Sun is at its most active with sunspots blooming, flares erupting and dynamic solar winds interacting with the atmosphere of Mars. For the scientists on the MAVEN project, it was an opportunity to gather the greatest range of data, as the Sun won't provide an easier opportunity to study these interactions for several years.

MAVEN will by no means be able to prove or disprove whether or not life once existed on the Red Planet, but by showing us where the atmosphere went and how that may have happened, Beutelschies thinks we're well on the way: "If MAVEN provides us with results that say, 'we can see that the atmosphere would have been this warm', 'this wet' or 'supporting liquid on the surface for this geologic amount of time' that will help answer some of the questions about the viability of life on Mars. Until we get that big 'dinosaur fossil', that's what will definitely help answer that question."

"We're getting at questions related to the habitability of Mars by microbes," explains Jakosky. "But the underlying question is whether there was ever life on Mars. I believe that addressing this question is the next step after MAVEN."

THE MARS ATMOSPHERE AND VOLATILE EVOLUTION PROBE



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MARS

25 AMAZING DISCOVERIES

IT IS OVER 50 YEARS SINCE THE FIRST SPACECRAFT FLEW PAST MARS AND, IN THAT TIME, WE HAVE LEARNT A HUGE AMOUNT ABOUT OUR MYSTERIOUS RED NEIGHBOUR

Words Laura Mears

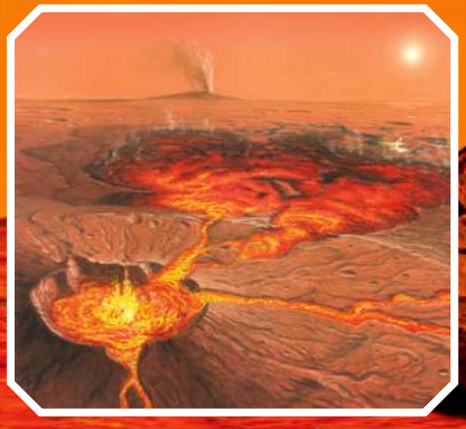
A MASSIVE VOLCANO

ITS ANCIENT WATERWAYS

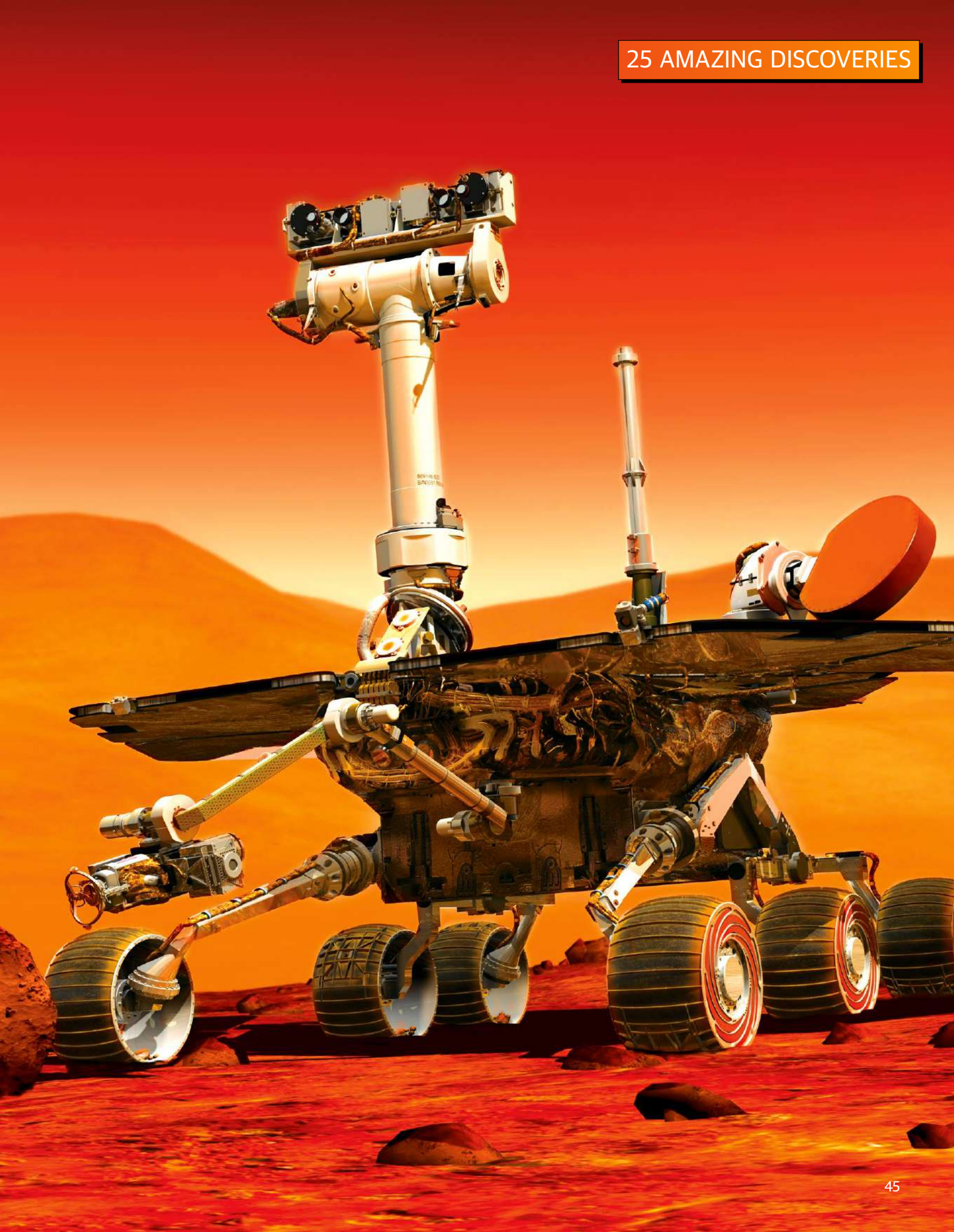
THE MELTING POLAR ICE CAPS

A NEAR-MISS

THE DANGERS OF EXPLORATION



ITS VIOLENT HISTORY



1 MARS LOOKS LIKE A DEAD PLANET

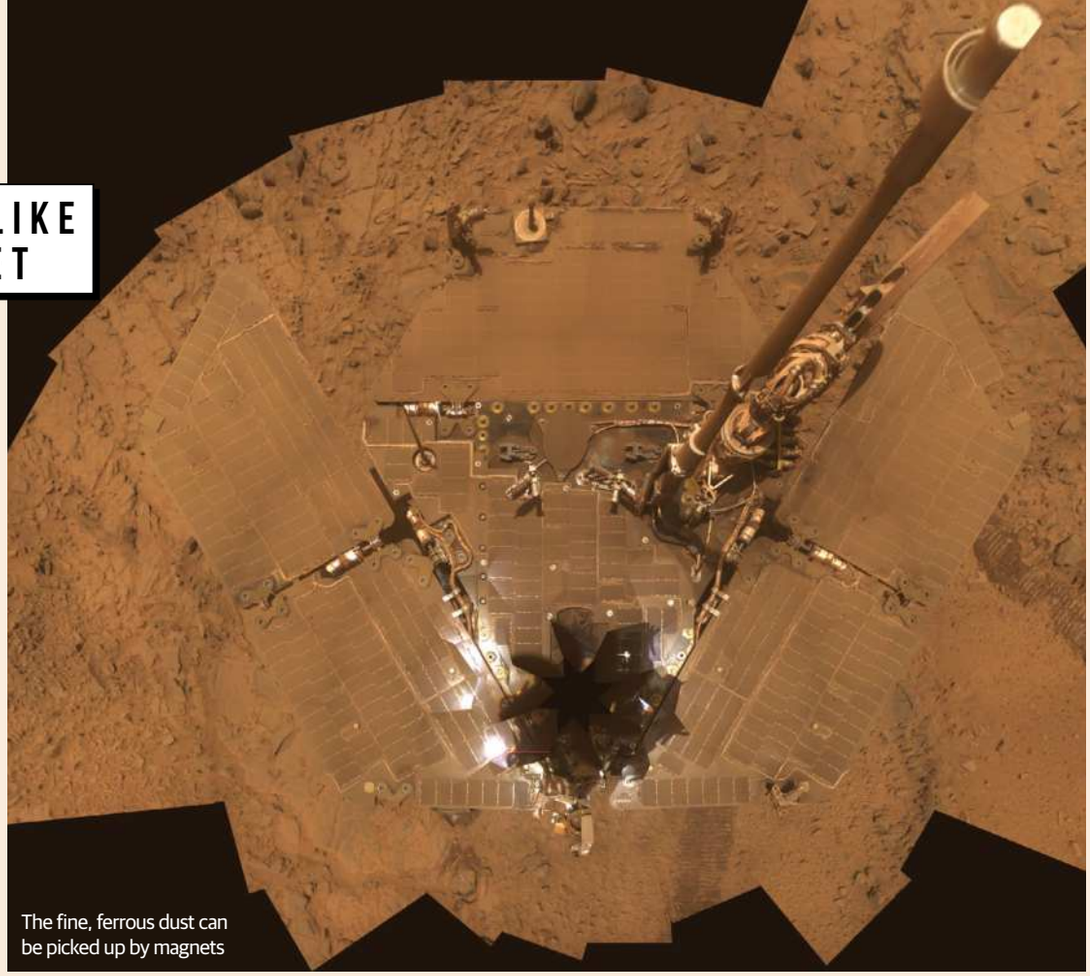
Astronomer Schiaparelli observed 'channels' on Mars

Since the invention of the telescope in the 1600s, astronomers have been fascinated by the surface of Mars. It is too far away to resolve from the Earth, and the atmospheres of both planets interfere with the passage of light, but many observers noticed dark and light patches that moved as the year passed, and speculated that they might belong to clouds, seas and even forests.

In the 19th century, Italian astronomer Giovanni Schiaparelli described a series of channels that he saw in the surface of the planet, imagining that there might be water on the surface, but a mistranslation of the Italian word 'canali' led American scientists, most notably Percival Lowell, to believe that the Red Planet was actually covered in real canals, that were possibly built by an intelligent life form.

Hopes of an Earth-like planet were dashed when NASA's Mariner 4 captured the first ever close-up images of the surface during a flyby in 1965. The 22 stills showed craters, reminiscent of the scarred surface of the Moon, and revealed the planet to be a barren waste covered in red dust and rubble. Measurements taken by the onboard instruments detected no magnetic field, and barely any atmosphere.

For years after, scientists thought Mars was a dead planet, whose geological activity stopped billions of years ago. But subsequent missions revealed that there's much more to Mars than meets the eye.



The fine, ferrous dust can be picked up by magnets

2 MARTIAN DUST IS MAGNETIC

The Red Planet owes its distinctive colouration to large amounts of iron, which was detected in high quantities in the soil by the Viking landers in 1976. Its surface is coated in a fine layer of dust, which after billions of years of winds and storms has been ground down to a consistency finer than talcum powder. The Imager for Mars Pathfinder (IMP), attached to the Carl Sagan Memorial Station, which landed in 1997, used the difference in atmospheric brightness throughout the day to measure the size of the airborne dust particles, revealing that on average, they measure about three microns in diameter: the perfect size to interfere with delicate equipment!

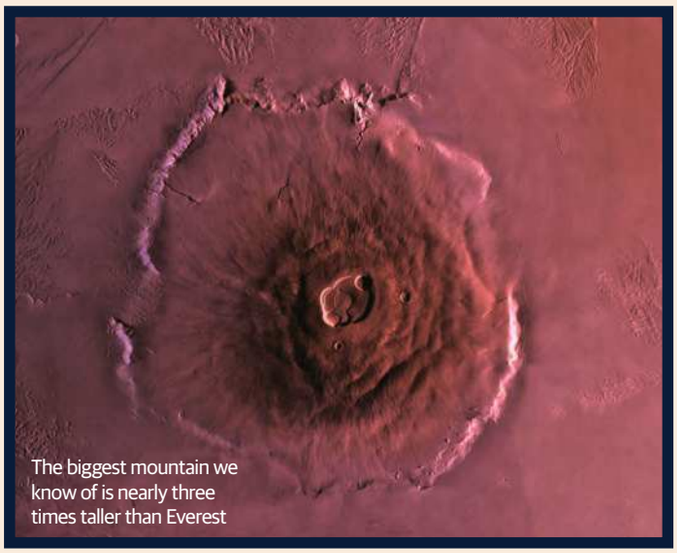
In 2004, NASA's Spirit rover carried permanent magnets to the surface of the planet to probe the dust further, confirming that almost all of the dust on Mars is magnetic, whether in the air or on the ground. Two angled magnets captured particles from the atmosphere, revealing different oxides of iron; strongly magnetic dark material that is either magnetite or maghemite, plus lighter, less magnetic haematite. The rover also carried a strong magnet near its panoramic camera that repelled the dust, protecting the equipment and ensuring the images remained clear.

MISSION PROFILE

Mariner 4

Launched: 28 November 1964
Arrived at Mars: 14 July 1965
Weight: 260.68kg (574.70lb)
Number of days on/around Mars (in Martian days and Earth days): 1 day/1 day
Current status: Communications terminated in 1967

3 IT IS HOME TO THE TALLEST MOUNTAIN IN THE SOLAR SYSTEM



The biggest mountain we know of is nearly three times taller than Everest

The first orbiter to visit Mars was NASA's Mariner 9, tasked with mapping 70 per cent of the planet's surface. However, when it arrived in 1971, the planet was engulfed in a dust storm that completely obscured the view of the ground below, and the orbiter had to wait for several months for the dust to settle.

As the storm subsided, the highest points were revealed first, and four enormous volcanoes started to appear above the sinking clouds. They were large and domed in appearance, and the sides had gentle slopes, reminiscent of the shield volcanoes on Earth.

The lava in shield volcanoes is lower in silica than the lava in stratovolcanoes, making it runnier and more liquid. Instead of spraying outwards, as it escapes through the crust it moves in fluid sheets, and the lava flows travel for great distances across the ground. Over time, a gentle slope builds up as layer upon layer of lava are laid down, resulting in a wide, smooth volcano.

The tallest of the Martian shield volcanoes is Olympus Mons, measuring 624 kilometres (374 miles) across and extending nearly 26 kilometres (16 miles) above the ground. It easily dwarfs every other peak identified in the Solar System to date. For comparison, the tallest volcano on Earth, Mauna Kea in Hawaii, extends 10,000 metres (32,800 feet) above the floor of the Pacific Ocean.

4 MARS HAS TWO SATELLITES

The two moons of Mars are named Phobos and Deimos, after the sons of the Greek god of war, Ares. Phobos has the closest orbit of any known moon, and passes within 6,000 kilometres (3,730 miles) of the surface of the Red Planet, completing a full circle three times every day. They have been photographed close up by several missions, but never visited.

5 MARS USED TO HAVE LAKES AND STREAMS

Mars wasn't always as dusty and desolate as it is today. Maps made of the surface by Mariner 9, the Viking orbiters, and the Mars Global Surveyor reveal networks of valleys across the southern hemisphere, and show evidence of streams running down the sides of the mountains.

The most convincing evidence for liquid water on Mars has been provided by NASA's rovers Spirit, Opportunity and, more recently, Curiosity. Within just a few months of landing in Gale Crater, Curiosity revealed an ancient streambed. On the ground are dunes made from sand and pebbles, too heavy to have been moved by the winds in the thin Martian atmosphere. The pebbles were smooth, like those you might find at the beach, and in the nearby rocks were veins of calcium sulphate, a mineral that would have been dissolved in the water that once flowed there. The rover also came across the site of an ancient lake, containing clay minerals formed in neutral water and mudstone, made from particles laid down over time.

In 2014, Opportunity discovered another fresh water source on Mars, 8,000 kilometres (4,970 miles) away from the Curiosity site and positioned in rocks from the earliest point in Martian history, when the surface was likely to have been more similar to Earth. The rocks in the area are smectite, a clay mineral formed in the presence of pH-neutral water.

3.5 billion years ago

Mars underwent a catastrophic change, and within the space of a few hundred million years, its core cooled, its magnetic field was lost, and over 95% of its atmosphere boiled away, preventing liquid water from existing on the surface. Over the next 3 billion years, volcanic activity periodically melted ice trapped beneath the surface, forming channels and gullies.

4 billion years ago

In the earliest history of Mars, the heavy bombardment was battering the inner planets of the Solar System, creating the craters now visible on Mars' southern hemisphere. The planet still had its atmosphere, and liquid water existed on the surface, possibly as a vast ocean that covered the northern hemisphere.

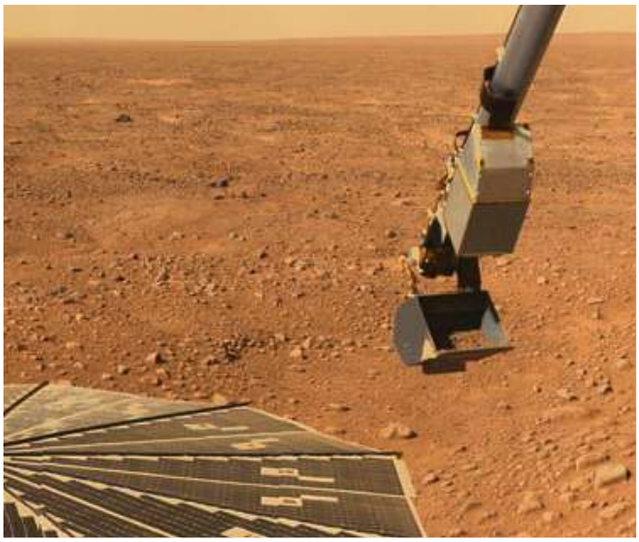
MISSION PROFILE

Opportunity

Launched: 7 July 2003
Arrived at Mars: 25 January 2004
Weight: 185kg (407.9lb)
Mission type: Search for past water activity on Mars
Current status: Lost contact 10 June 2018

7 MARS ISN'T ROUND

NASA's Mars Global Surveyor spent three years creating a topographical map of the entire Martian surface. It revealed that the northern hemisphere is low and flat, while the southern hemisphere is high, rugged and cratered, with a huge difference in elevation between the top and bottom of the planet.



6 IT WAS ONCE CAPABLE OF SUPPORTING LIFE

The sedimentary rocks laid down over millions of years on the surface of Mars are evidence that liquid water existed for prolonged periods, giving plenty of time for life to have evolved. Following the repeated discovery of water on Mars, NASA switched its focus to searching for signs of life, and the Curiosity rover has been hunting since it landed in 2012.

It has drilled into the sedimentary rocks in a location called Yellowknife Bay, revealing that the minerals beneath contain nitrogen, phosphorous, hydrogen, oxygen, carbon, and sulphur – the building blocks of the biological molecules that make up all life on Earth. On our own planet, microorganisms known as lithoautotrophs (rock eaters) can survive by using inorganic molecules to obtain their energy.

As the climate on Mars changed, the liquid water on the surface became trapped in the soil as permafrost, and today nothing can survive on the surface. The planet is bathed in radiation, battered by solar winds, and the atmosphere is painfully thin. However, on Earth bacteria can survive buried deep in Antarctic permafrost. Scientists are hopeful that if there was once life on Mars, traces will remain in the ice.

Present day

The atmosphere on Mars is thin, and the vapour pressure is low. Any water ice reaching the surface instantly sublimes into vapour and escapes. Much of the water that used to cover the planet is trapped beneath the ground as permafrost, and missions are ongoing to determine whether there is liquid water hidden below.

MISSION PROFILE

Curiosity

Launched: 26 November 2011
Arrived at Mars: 5 August 2012
Weight: 899kg (1982lb)
Mission type: To determine whether Mars could have supported life in the past
Current status: Active

8 A DAY ON MARS IS 41 MINUTES LONGER THAN A DAY ON EARTH

Mars missions are planned and executed according to Mars time, where a day lasts for 24 hours and 37 minutes (compared to the 23 hours and 56 minutes of an Earth day). Amazingly, this number has been known since 1666, when Giovanni Cassini calculated the planet's spin by watching surface features appear and disappear (he estimated the Martian day length to be 24 hours and 40 minutes).

9 ITS GRAVITY IS ABOUT A THIRD OF EARTH'S

The orbital behaviour of satellites around Mars, both natural and artificial, have revealed that there is 62 per cent less gravity on Mars than there is on Earth. Mars is just half the size of the Earth, and is only around 11 per cent of the mass, dramatically reducing its gravitational pull.

10 A VAST CANYON OPENED UP AS THE CRUST STRETCHED

One of the most striking features on the surface of Mars is Valles Marineris, named after the Mariner 9 orbiter that discovered it. The vast canyon stretches across the equator and is over 4,000 kilometres (2,485 miles) in length, seven kilometres (four miles) deep and is thought to have been formed when the planet cracked as it cooled.

NASA's Gaylon McSmith, current project manager for Mars Odyssey Explorer, which revealed water ice beneath the Martian poles

11 THE GROUND IS FILLED WITH WATER ICE

One of the major questions surrounding Mars was what had happened to its water. Today, there may be trickles of liquid on the surface but it instantly sublimes into vapour, before escaping the atmosphere into space. However, in the past the planet was covered with lakes, streams and possibly even oceans.

Between 2001 and 2002, the Mars Odyssey Explorer looked for hydrogen beneath the surface of Mars, evidence that there might be trapped water. The map it returned revealed that beneath the dry carbon dioxide ice at the poles there is a huge quantity of water ice. The radar sounder onboard ESA's Mars Express orbiter later revealed that there is enough potential water trapped under the Martian poles to cover the entire planet in an ocean 11 metres (36 feet) deep.

"IN THE PAST THE PLANET WAS COVERED WITH LAKES, STREAMS AND EVEN OCEANS"

12 THE CORE MIGHT STILL BE MOLTEN

The lack of magnetic field around Mars indicates the core might have solidified, but the Mars Reconnaissance Orbiter revealed evidence of plate tectonics, with features some scientists say are reminiscent of the San Andreas fault in California, where two plates are moving horizontally past each other.

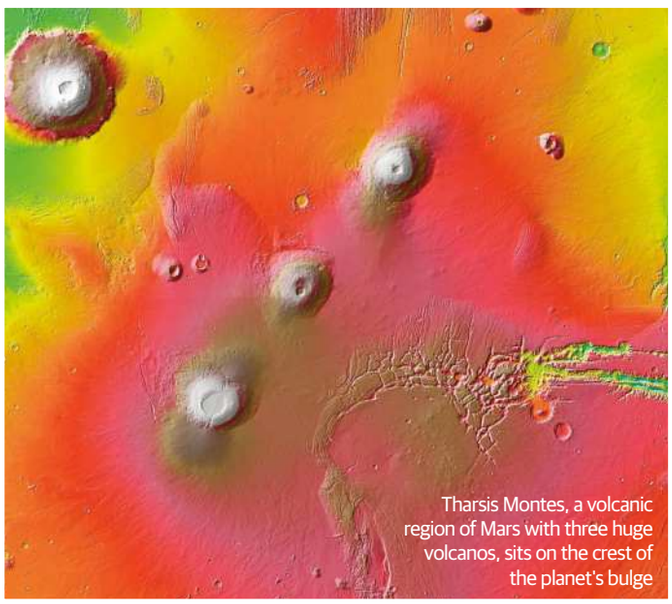
At Mars' permanent south pole, winter temperatures plummet as low as -153C (-243F)

13 MARS HAS SEASONS

Seasons represent changes in day length and climate throughout the year, and are dependent upon a planet's distance to the Sun. If a planet is spinning straight up on its axis the equator always gets the same amount of sunshine every day, but if the planet is tilted the daylight hours vary slightly throughout the year. Earth is tilted on its axis by a little over 23 degrees, and Mars by 25 degrees, and both experience seasonal variations.

Mars differs from the Earth in that it has a more elliptical orbit and at certain times of the year is much closer to the Sun. As a result, spring and summer are longer in the northern hemisphere than they are in the southern, because when the north is tilted towards the Sun on the axis the entire planet is farther away in its orbit and so travels slower.

While the northern hemisphere enjoys a long summer, the winters at the southern hemisphere are harsh, and for much of the time the south pole is in complete darkness. The temperature drops so low that carbon dioxide solidifies out of the air, forming a permanent cap of dry ice over the region. NASA's first ever landers to reach the surface of the Red Planet, Viking 1 and Viking 2, showed that atmospheric pressure drops by as much as 25 per cent as the gas freezes in the Martian winter.

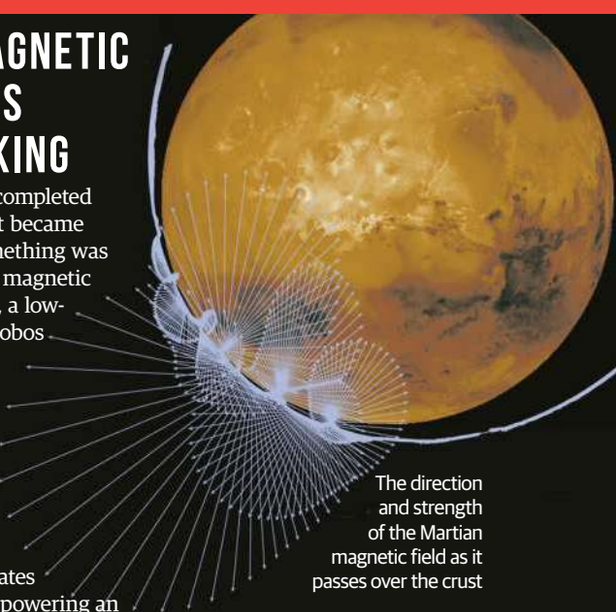


Tharsis Montes, a volcanic region of Mars with three huge volcanos, sits on the crest of the planet's bulge

14 IT HAS SHIFTED ON ITS AXIS

NASA's Mars Global Surveyor completed a full map of the surface of Mars in 2001, but something didn't quite match up. The positions of the shorelines where regions of water might have been weren't level. A team at the University of California, Berkeley showed that the shoreline movement might be down to the change in the spin axis of Mars. The spin axis of Mars is not fixed like Earth's, but has changed over its lifetime, and crust has moved relative to the axis over a distance of around 3,000 kilometres (1,864 miles) along the surface in the last 2 to 3 billion years. As planets spin the motion causes them to bulge in the centre, and the group calculated that deformation in the crust would have changed the water level to match the patterns seen in the shorelines. It is even thought that floodwater might have contributed to the tilting of the planet, tipping the planet by 50 degrees, and then tilting it back again by 20 degrees as it dried out.

15 ITS MAGNETIC DYNAMO IS NOT WORKING



The direction and strength of the Martian magnetic field as it passes over the crust

When Mariner 4 completed its flyby in 1965, it became apparent that something was wrong with Mars' magnetic field, and by 1989, a low-orbiting probe, Phobos 2, sent to Mars by the Soviet Union had revealed that it is 3,000 times weaker than the Earth's.

Earth has a molten iron outer core, which circulates inside the planet, powering an internal magnetic dynamo. It acts like a giant bar magnet, generating magnetic field lines that spring out from the poles and encircle the Earth, deflecting solar winds and helping to protect the atmosphere. On Mars, these field lines are missing and, rather than circling the planet, weak magnetic fields are fixed in specific locations, mainly in the southern hemisphere. Earth's magnetic field periodically changes direction, and its magnetic history is written in to the rocks, with alternating bands of magnetic material deposited in opposite directions. NASA's Mars Global Surveyor found similar striped magnetic field lines in the ground of the southern highlands, indicating that at some point Mars had a functioning dynamo. These stripes are absent from the northern hemisphere, which formed much later in the history of the planet, suggesting the dynamo stopped functioning a few hundred million years after Mars formed.

16 MARS IS STILL LOSING ITS ATMOSPHERE

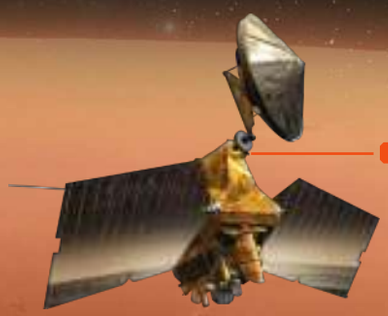
The atmospheric pressure on Mars ranges from around five to ten millibars (compared to 1,000 millibars here on Earth). The Red Planet is around 50 per cent smaller in diameter than Earth, and its lower gravity would have allowed the outer layers of the atmosphere to escape early in its life, particularly during energetic asteroid collisions. As the atmosphere started to thin, it would have provided less resistance to incoming asteroids, which would have resulted in even more collisions, beginning a vicious cycle of atmospheric loss. Without a functioning magnetic field, the Red Planet is also vulnerable to the distruptive effects of solar winds.

The Mars Express carries an imager capable of detecting the effects of solar winds, and showed that today, charged particles enter the Martian atmosphere, ionising the gases and allowing them to escape into space. NASA's Mars Atmosphere and Volatile Evolution (MAVEN) orbiter arrived on 21 September 2014, followed a few days later by India's Mars Orbiter Mission (Mangalyaan), and the two teams are collaborating to discover more about how Mars lost its protective sphere of gas.

MISSION PROFILE

Mars Global Surveyor

Launched: 7 November 1996
Arrived at Mars: 12 September 1997
Mission goal: To characterise the surface features and geological processes on Mars
Current status: Contact ceased November 2006



Mars Reconnaissance Orbiter

Comet Siding Spring gave Mars a spectacular show as it passed nearby in October 2014

17 IT HAD A NEAR MISS WITH A COMET

The comet Siding Spring was discovered in January 2013 and in October 2014, it passed within 139,500 kilometres (86,680 miles) of the surface of Mars, just under a third of the distance from the Earth to the Moon. At the time there were two active rovers on the surface of the planet (Opportunity and Curiosity) and five active orbiters. All pointed their cameras in its direction.

The dust from the tail of the comet could easily have damaged the orbiting spacecraft, so the active orbiters, Mars Express, Mars Orbiter Mission, Mars Odyssey, Mars Reconnaissance Explorer and MAVEN waited on the opposite side of the planet. The comet passed without incident, and four orbiters managed to take pictures as it went.

18 DUST STORMS CAN SHROUD THE ENTIRE PLANET

The dust that covers the surface of Mars is as fine as smoke and can float even in the painfully thin atmosphere. The biggest dust storm ever recorded on the Red Planet was seen by Mariner 9 when it arrived in 1971 and, since 1997, the Mars Global Surveyor has been in a polar orbit around Mars, tracking the planet's weather.

As the ground heats up in the morning each spring, dust devils begin to form. Energy from the Sun is absorbed by the dust and rocks and in turn starts to heat the gases. They then rise up through the cold air, creating a spinning vortex. NASA says that the atmosphere is so thin that you wouldn't feel much wind on Mars, but that the fine dust whips through the air, building up static and releasing electrical arcs. As the day cools the storms subside, but the tiny dust particles can fly tens of kilometres into the air. In the low gravity, it takes a long time for them to fall back down to the surface again, with some remaining airborne for months.

The surface of Mars prior to (top) and during (above) the 2001 global dust storm as captured by Hubble

Upper
As you move up through the Martian atmosphere the pressure drops rapidly and the temperature rises. At altitudes of above around 200km (124mi), the gases begin to tail off into space, with no clear boundary between the atmosphere and the vacuum.

Middle
The combined effect of the spin of the planet, and the heating and cooling of the gases and dust in the atmosphere creates jetstreams between the lower and upper layers of the atmosphere. A similar effect can be seen on Earth.

Lower
In the lower atmosphere, dust particles absorb heat from the Sun, warming the air to around -63°C (-82°F). Clouds of water ice and carbon dioxide form in this layer, and dust storms regularly fill the air.

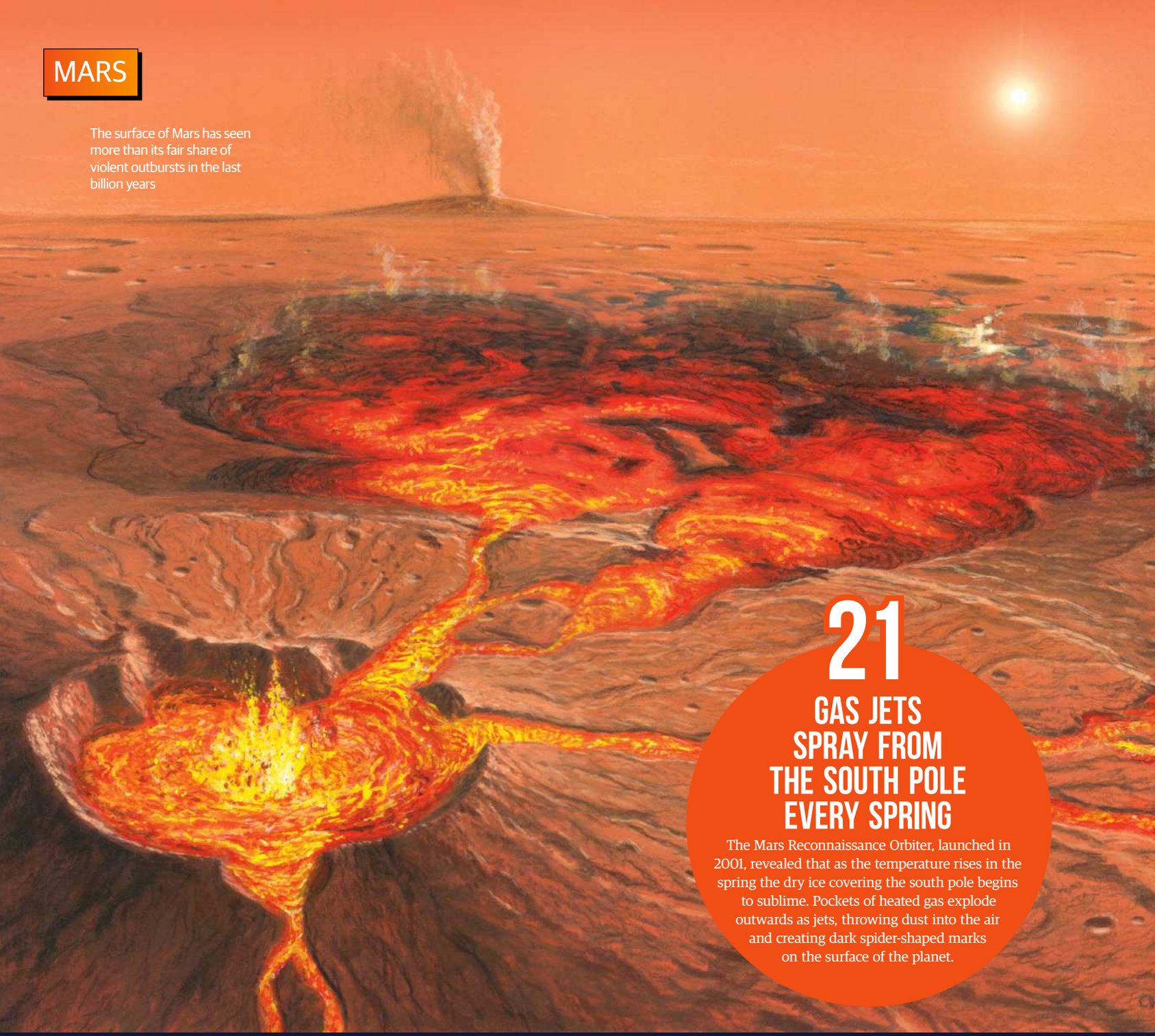
19 MARS HAS CARBON DIOXIDE WEATHER

The atmosphere on Mars was first analysed during the Mariner 4 flyby, and has been tested by several orbiters since. The first accurate measurements of its composition were made by the Viking landers, revealing that the thin air is 95.32 per cent carbon dioxide, 2.7 per cent nitrogen, and 1.6 per cent argon. Just 0.13 per cent of the atmosphere is oxygen, and 0.03 per cent is water vapour. In contrast, the atmosphere on Earth is 78 per cent nitrogen, 21 per cent oxygen, and just 0.04 per cent carbon dioxide.

The European Space Agency launched its Mars Express orbiter in 2003, and has been monitoring the atmosphere ever since. It has observed carbon dioxide clouds forming around 80 kilometres (50 miles) in the air above the equator, and watched as it freezes down to cap the poles each winter. The orbiter also detected traces of methane gas alongside water vapour, sparking scientific interest in the potential for volcanic activity, or even life, beneath the surface.

MISSION PROFILE
Mars Express

Launched: 2 June 2003
Arrived at Mars: 25 December 2003
Weight: 113kg (249lb)
Mission goal: To image the entire surface of Mars at super-high resolution
Current status: Active



The surface of Mars has seen more than its fair share of violent outbursts in the last billion years

21 GAS JETS SPRAY FROM THE SOUTH POLE EVERY SPRING

The Mars Reconnaissance Orbiter, launched in 2001, revealed that as the temperature rises in the spring the dry ice covering the south pole begins to sublime. Pockets of heated gas explode outwards as jets, throwing dust into the air and creating dark spider-shaped marks on the surface of the planet.

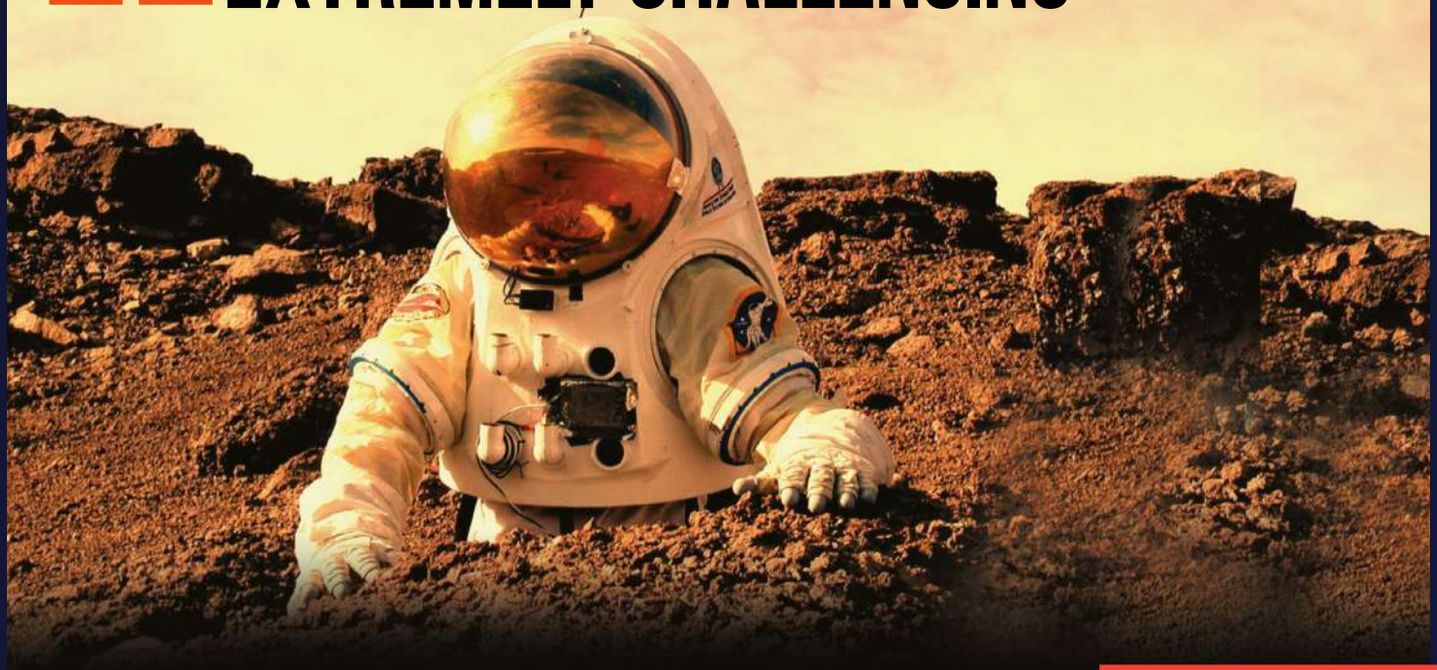
20 THERE HAS BEEN RECENT VOLCANIC ACTIVITY ON MARS

The history of Mars is mapped out in the rocks that cover its surface and, using data gathered from orbiters and landers, scientists are beginning to piece together the planet's past. Over time, conditions on the surface have changed dramatically.

The Mariner 4 spacecraft observed some of the planet's oldest regions, craters made in the southern hemisphere during the heavy bombardment that battered the rocky planets around 4 billion years ago. Although this part of the surface has remained largely unchanged, the rest of the planet has since been remodelled. The northern hemisphere is much less cratered and has been covered with smooth lava plains, and the tops of the shield volcanoes at the equator indicate that they were recently active. Lava flows from the volcanoes repeatedly covered up impact craters, and by looking at the calderas at the top of the mountains it is possible to estimate when they last erupted. ESA's Mars Express has been examining the volcanoes, and scientists estimate that volcanic activity continued until 100 to 200 million years ago, with evidence of lava flows within the last few million years. It may be that the volcanoes are dormant, not extinct.

"SHIELD VOLCANOES AT THE EQUATOR WERE RECENTLY ACTIVE"

22 TRAVELLING TO MARS IS EXTREMELY CHALLENGING

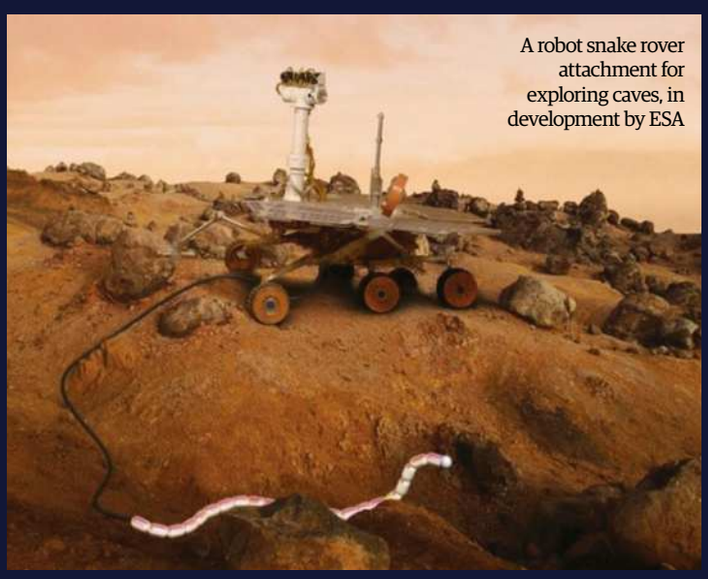


It will be far trickier to safely send astronauts to Mars than it was to send them to the Moon

If there is one thing that we have learnt about Mars over the last 50 years of space exploration, it is that travelling to the Red Planet is incredibly difficult. The first flyby in 1965 was the seventh attempt at reaching the planet and, since then, several more orbiters and landers have been lost. In the Nineties, four of NASA's six missions to the Red Planet failed. In 2003, the European Space Agency lost the Beagle 2 Lander launched alongside the successful Mars Express. And Russia and China's joint effort Phobos-Grunt/Yinghuo-1 was trapped in orbit around Earth in 2011.

Those that did reach the Red Planet had problems of their own. Although the Phoenix lander outlasted its three-month mission, its solar panels were eventually destroyed by the weight of many tens of kilograms of dry ice during the winter and, after six years on the surface, a wheel on NASA's Spirit rover stopped working, causing it to become irrevocably trapped in the Martian sands in 2009. More recently, NASA's Curiosity rover experienced unexpectedly quick damage to its aluminium wheels, forcing scientists to drive it in reverse.

But despite all these problems, we have learnt a huge amount about Mars and the combined information from both the successes and failures is being assembled and used to inform current and future missions. Using the information we have acquired, NASA intends to take humans to Mars in the 2030s.



A robot snake rover attachment for exploring caves, in development by ESA

23 THERE ARE CAVES ON MARS

In 2007, the infrared cameras of the Mars Odyssey Orbiter spotted a set of caves on the surface of Mars, dubbed the Seven Sisters. They are located on the side of one of the shield volcanoes, Arsia Mons, and are visible as 'skylights', extending tens of metres downwards into lava tubes or sinkholes. Caves on Mars could provide easier access to buried layers of ancient rock without the need for heavy-duty drilling. These sheltered areas might be a good place for us to search for evidence of past life on the planet.

24 SUNSETS ARE PURPLE ON MARS

The Viking 1 lander returned the first images of the Martian sunset in the Seventies. The fine red dust particles tint the sky a pinkish colour in the evening, but as the Sun starts to dip below the horizon, blue light is scattered, creating a purplish hue.

25 MARS HAS OZONE LAYERS

ESA's Mars Express orbiter has been circling the planet since 2003, and is equipped with a UV spectrometer called SPICAM. It's shown that Mars has an ozone layer at an altitude of 30 kilometres (19 miles), another in the northern spring/summer at between 30 to 60 kilometres (19 to 37 miles), and a third above the south pole in winter at around 40 to 60 kilometres (25 to 37 miles).

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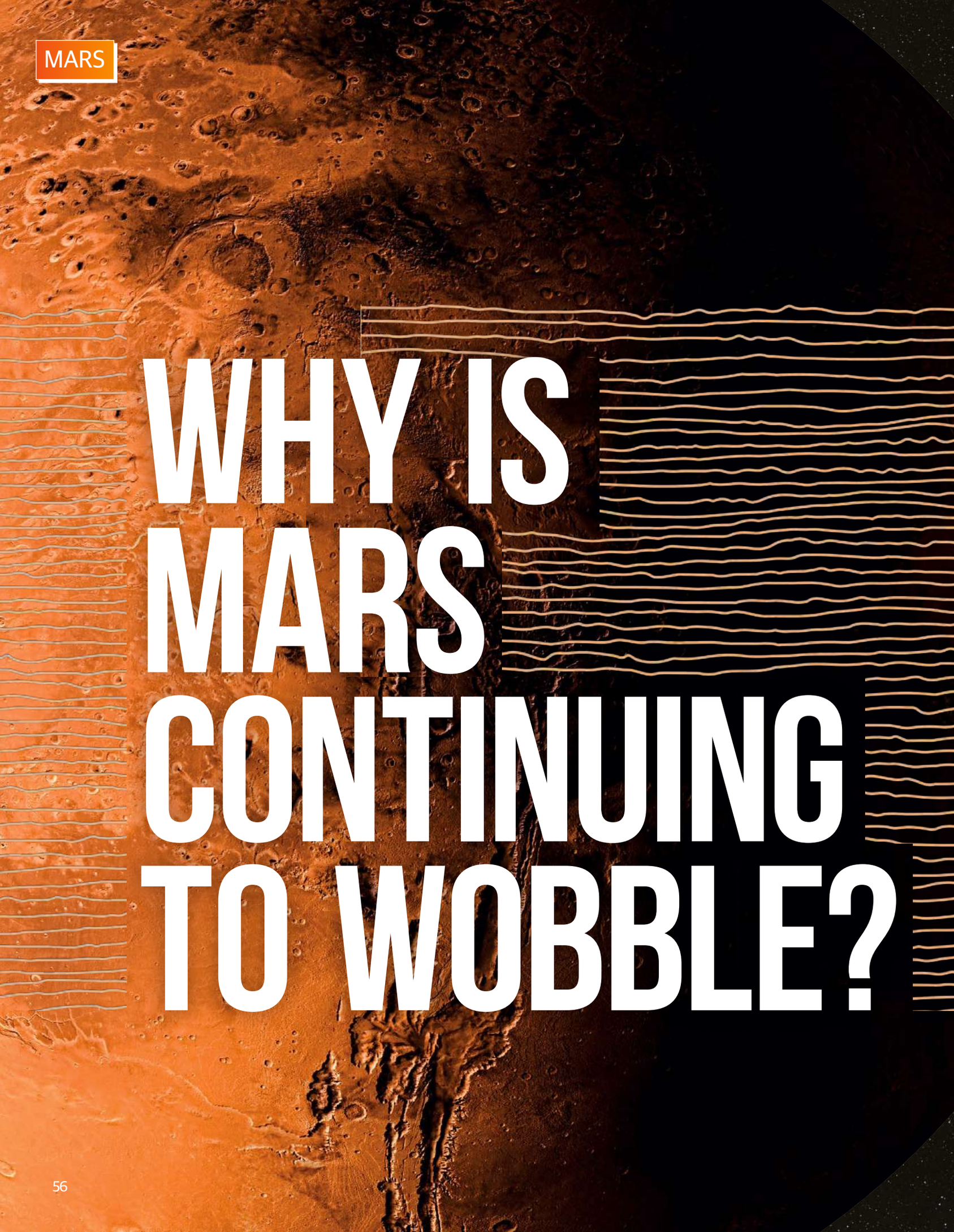


WHY IS MARS CONTINUING TO WOBBLE?

RESEARCHERS CONFIRM THAT THE RED PLANET IS SPINNING OFF ITS AXIS

Words David Crookes

Grab your telescope and gaze at Mars. Are you able to spot something unusual as you focus in on the planet, paying particular attention to its white caps? Not even a little bit? Here's a clue: we're referring to a teeny, tiny wobble that occurs as the poles wander from the Red Planet's axis of rotation. Still can't see it? Don't worry – it's taken scientists decades to spot some rather odd behaviour on the Red Planet.

For the past 18 years, radio tracking observations determined from satellites orbiting the planet have been able to show stark evidence of the Chandler wobble on Mars – a variation of latitude named after American astronomer Seth Carlo Chandler, who discovered the phenomenon in 1891. In simple terms, it means the Red Planet is repeatedly wobbling as it spins, in this case by just ten centimetres (four inches) from the planet's axis of rotation – that's why you're unlikely to see it for yourself. If you're after a nailed-on explanation of why it's continuing to happen, then you're sadly out of luck.

Although scientists have made a breakthrough in determining that the Red Planet wobbles in its rotation, they are not exactly sure what is driving it. What they've gleaned from studying the data so far is that the Chandler wobble on Mars occurs in a near-circular, counterclockwise direction, as viewed from its north pole, every 207 days. As a result, the poles don't always line up perfectly. The Red Planet is the only other body in the universe known to exhibit such behaviour, with the phenomenon only ever discovered and confirmed on Earth before.

It makes the new discovery highly significant, and not just because there are now two planets resembling a spinning top teetering as it loses speed. This latest study shows the sheer importance of gathering and analysing information over a long period of time – a laborious process requiring heaps of patience, but one that in this case has proven ultimately rewarding.

"With 18 years of data, the Chandler wobble signal is very clear," explains Alex Konopliv, an aerospace engineer at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. And as more data comes through, the better the conclusions will become.

Before we take a closer look at the Chandler wobble on Mars, let's first briefly examine its effect on Earth by way of comparison. We know that our planet rotates on its axis every 24 hours – every 23 hours, 56 minutes and four seconds, to be exact – but while you may excitedly spin a globe on your desk and smoothly reach a destination when it comes to a halt, real life isn't quite like that.

On Earth, the poles repeatedly wander away from the average axis of rotation by as much as nine metres (30 feet) every 433 days. We don't feel it, of course, and the only downside is

> "WITH 18 YEARS OF DATA, THE CHANDLER WOBBLE SIGNAL IS VERY CLEAR"
> ALEX KONOPLIV

© Alamy, Getty

CHANDLER WOBBLE BY NUMBERS

10
Amount Mars' poles wander in centimetres

207
Repeated cycle of the Chandler wobble on Mars in days

18
Years of data taken to determine the Chandler wobble on Mars

NINE
Maximum off-centre motion, in metres, of the Chandler wobble on Earth

433
Repeated cycle of the Chandler wobble on Earth in days

TWO
Number of planets confirmed to exhibit signs of the Chandler wobble

1891
Year the Chandler wobble was discovered

63
Maximum number of years the wobble should take to freely decay if not excited

that the wobble needs to be considered when observing Earth or working with GPS. But one thing is certain: it is much more perceptible than the very slight wobble discovered on Mars, so how did the scientists reach their conclusion given such circumstances?

The answer comes in the form of NASA satellites, which have been orbiting Mars for different reasons. The Mars Global Surveyor, for instance, was used to map the entire planet between 1999 and 2006. Mars Odyssey has been seeking evidence of water and ice while studying the planet's geology and radiation environment since 2001. And the Mars Reconnaissance Orbiter has been looking for potential future landing sites since 2006.

Konopliv tells All About Space that researchers have been able to collect enough precise information from these satellites to calculate the effects of gravitation on the orbits of the spacecraft. They've determined the pole motion from radio tracking observations, and it's led to a better understanding of the planet. "The Chandler wobble was detected because it affects the orbit of spacecraft at Mars," Konopliv affirms. "It mostly causes a slight oscillation of the orbital plane of a spacecraft with a period of a Mars day."

The method has been detailed in a study recently published by the American Geophysical Union in its peer-reviewed scientific journal, *Geophysical Research Letters*. "The size of the oscillation changes slowly over the months and years, and we see it as a time-varying signature in the Mars gravity field," Konopliv continues.

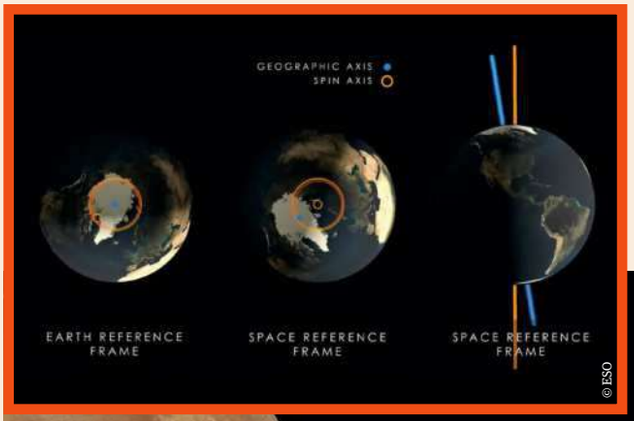
> "THE CHANDLER WOBBLE AFFECTS THE ORBIT OF SPACECRAFT AT MARS"
> ALEX KONOPLIV

"This signature is detected using Doppler tracking data of the spacecraft from the NASA Deep Space Network of stations. [It measures the spacecraft's speed along the direction from Earth's tracking station to the spacecraft.] Those measurements help us determine the spacecraft's orbit and how it changes over time."

Since the signal is incredibly small, and changes so slowly over time, having many years of highly accurate data has proved vital in the wobble's detection. "Additionally, there are other time-varying signatures in the gravity field that must be separated from the Chandler wobble signal," Konopliv says.

"These other signatures are due to the seasonal melting of the polar ice caps and the resulting movement of mass between the north and south poles. Our previous attempts with less data to detect the Chandler wobble were unsuccessful because we could not distinguish between the mass movement and the wobble."

But why does Mars wobble in the first place? Like Earth, which is 0.3 per cent thicker in the middle, the Red Planet - which is 0.6 per




© NASA

Above left: You can see here that the geographic and spin axes of Earth do not always match up, indicative of the Chandler wobble. The axes only match once every 6.4 years

Left: The amount of data amassed over 18 years ensured scientists could distinguish a wobble intrinsic to Mars' shape and interior from those potentially caused by outside factors

HOW MARS WOBBLES LIKE A SPINNING TOP

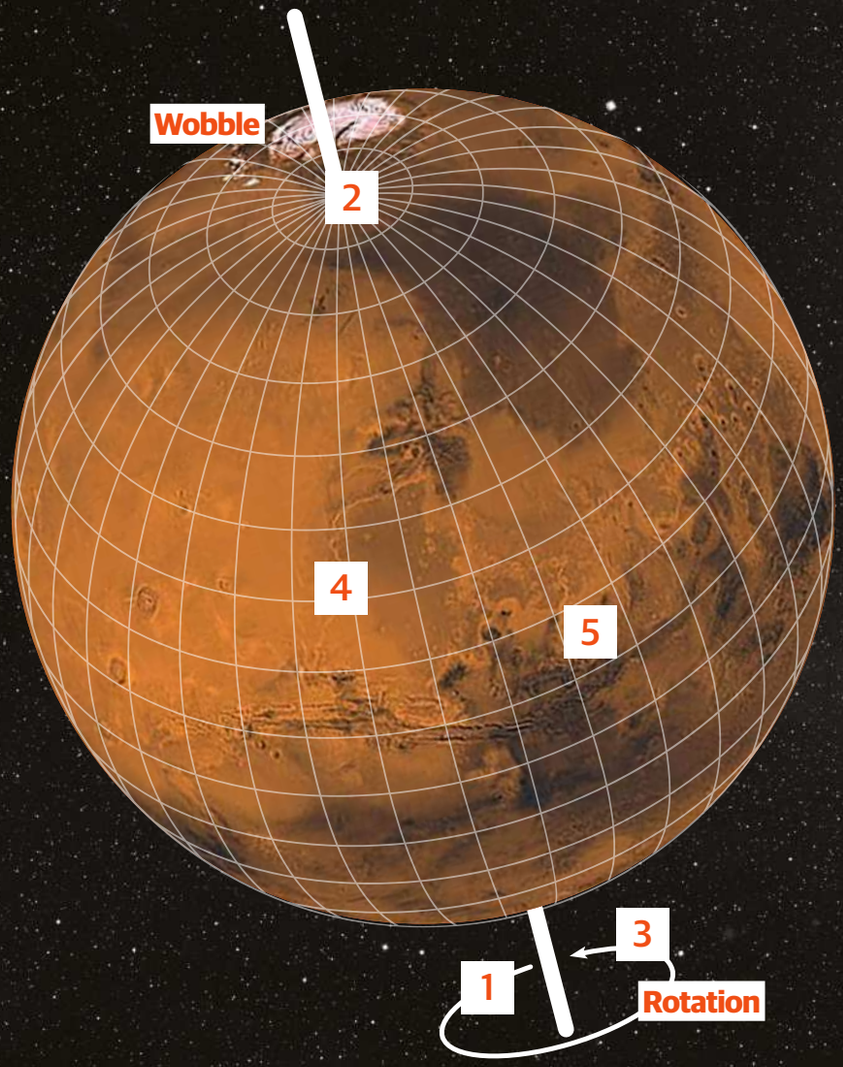
1 AXIS OF ROTATION
Mars rotates around its axis every 24 hours, 39 minutes and 35 seconds, which is slightly longer than on Earth, where the rotation takes 23 hours, 56 minutes and four seconds. This time defines a day on Mars, called a sol.

2 MARS' TILT
Mars is tilted 25.2 degrees relative to the plane of the Red Planet's orbit around the Sun. Because this is close to the 23.5-degree tilt here on Earth, it experiences similar seasons.

3 A SMALL WOBBLE
The wobble is only slight. It has an amplitude of ten centimetres (four inches) on the surface. When viewed from the north pole, it's in a near-circular counterclockwise direction.

4 TIME TAKEN
The wobble will complete its full circular deviation every 206.9 days, plus or minus half a day – a cycle that should, if no external moment is applied, die down with a time constant of between 7 and 63 years.

5 EXTERNAL INTERFERENCE
The fact Mars – which like Earth is not a perfect sphere – continues to wobble means it is being re-excited. This is likely due to atmospheric pressure changes.



© NASA/JPL; Getty

cent thicker – is not a perfect sphere, leading to imbalances that have an impact on both of these planets' spin. As such, it's determined that the Chandler wobble happens on planets that are not perfectly round, and this is why the phenomenon has long been thought to take place on planets other than Earth. It's just that scientists have not had firm evidence.

In the case of Mars, the spinning is understood to have begun due to seasonal atmospheric changes caused by the melting of the polar ice caps. If left alone, however, a planetary wobble of this nature should slow down over time. "The time to die down on Mars is the range of 7 to 63 years," Konopliv says, but that is not happening. So why exactly is that?

For Earth, past studies suggest the excitation of the wobble is likely due to pressure changes in the atmosphere combined with oceanic processes, keeping things moving. In 2000, for example, JPL geophysicist Richard Gross said that fluctuating pressure at the bottom of the ocean – which is caused by temperature and salinity changes – was the principal cause, along with wind-driven changes in the circulation of the ocean.

"The Chandler wobble of Earth is mainly excited by the oceans and the atmosphere," affirms Belgian geophysicist Véronique Dehant. Yet Mars does not have oceans, so could other external factors help explain the excitation? Maybe it could be due to the polar ice caps melting...

Konopliv thinks not. He says that the seasonal melting and reforming of the polar ice caps is an annual signal that is nearly repeatable. Taking into account that a Mars year is 687 days and a Chandler wobble period is 207 days, Konopliv says the wobble is shown to take place 3.3 times a year.

Right: The Mars Global Surveyor completed its mission in 2006 when it became unresponsive to messages and commands, but it was still able to provide radio tracking observations of the Red Planet

DETECTING MARS' NORTH POLE WOBBLE

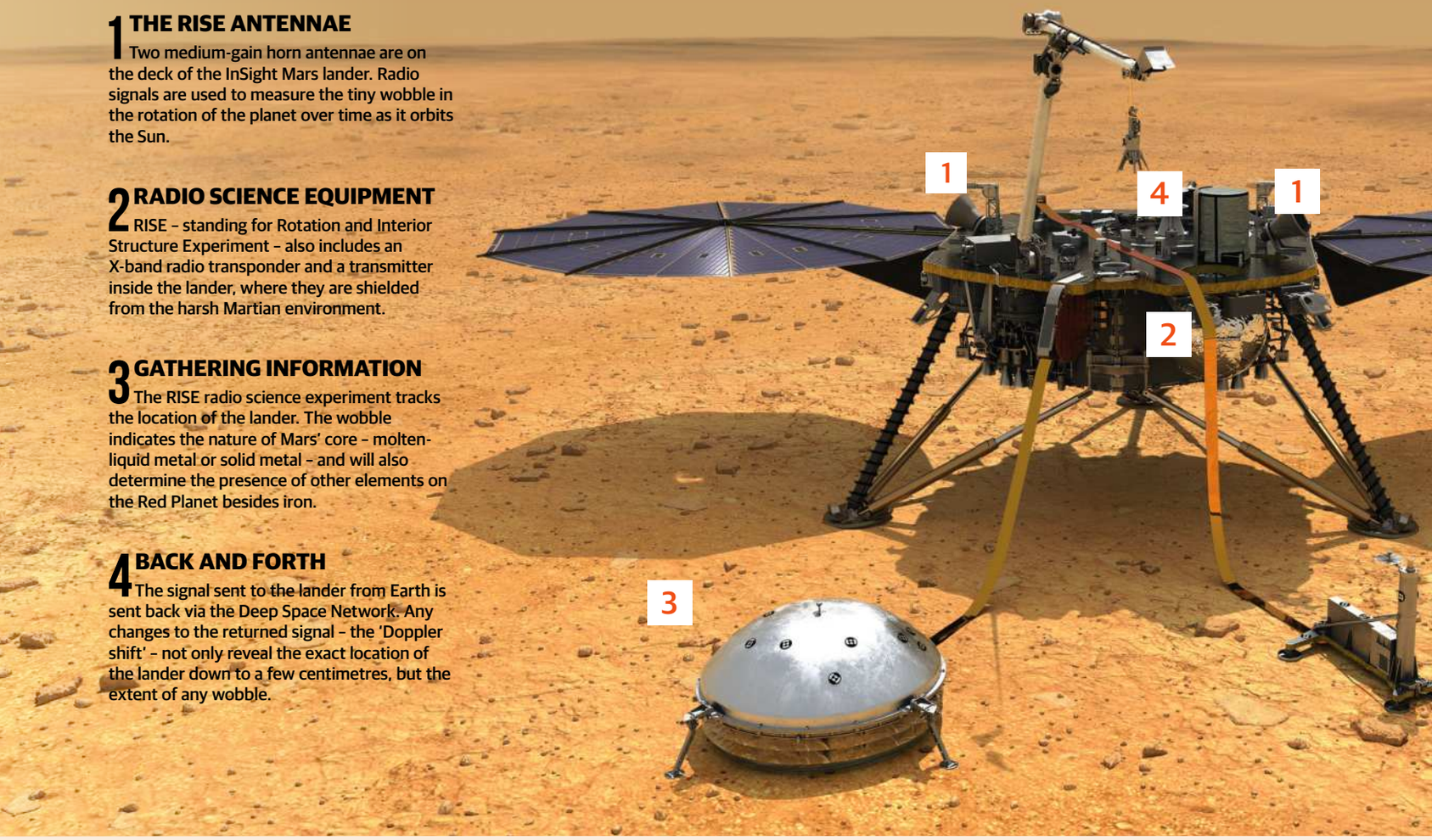
THE INSIGHT MISSION SEEKS TO PROVIDE PRECISE MEASUREMENTS OF THE PLANET'S MOVEMENTS

1 THE RISE ANTENNAE
Two medium-gain horn antennae are on the deck of the InSight Mars lander. Radio signals are used to measure the tiny wobble in the rotation of the planet over time as it orbits the Sun.

2 RADIO SCIENCE EQUIPMENT
RISE – standing for Rotation and Interior Structure Experiment – also includes an X-band radio transponder and a transmitter inside the lander, where they are shielded from the harsh Martian environment.

3 GATHERING INFORMATION
The RISE radio science experiment tracks the location of the lander. The wobble indicates the nature of Mars' core – molten-liquid metal or solid metal – and will also determine the presence of other elements on the Red Planet besides iron.

4 BACK AND FORTH
The signal sent to the lander from Earth is sent back via the Deep Space Network. Any changes to the returned signal – the 'Doppler shift' – not only reveal the exact location of the lander down to a few centimetres, but the extent of any wobble.



As a result, any mass signatures from melting polar caps would show exactly one, two, three or four times a year, and would be distinctly different from the wobble. "That is the reason why an extensive dataset is needed, because we've been able to separate the Chandler frequency from any third-annual signature," Konopliv says.

That just leaves pressure changes as the primary cause of the ongoing wobble. "For Mars, the principal excitation is likely of atmospheric origin," Konopliv explains. And yet the issue could still run deeper, with the motion driven by the properties of Mars' mantle, something which is being explored by Dehant. "To be detectable, the Chandler wobble requires the presence of a continuous forcing at a period close to that of the wobble," recaps Dehant. "The wobble of Earth is mainly excited by the oceans and the atmosphere, and for Mars, which doesn't have oceans, atmospheric processes are the main driver.

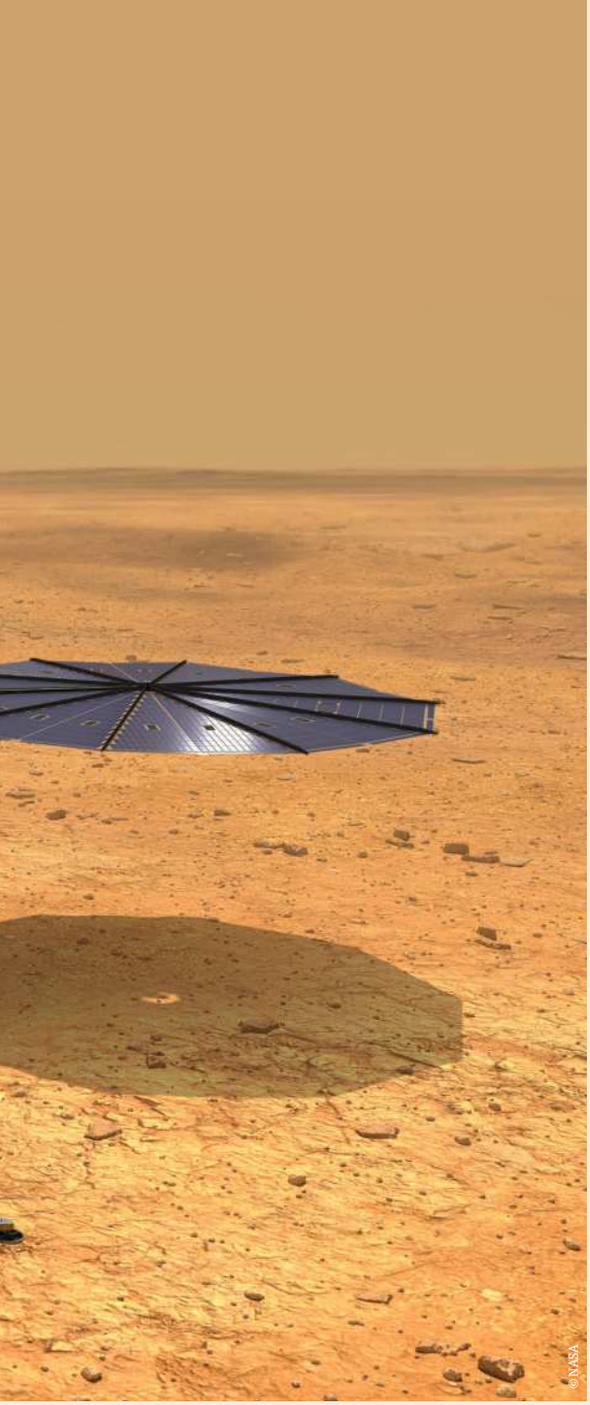
"Without forcing, the wobble would decay away after less than 100 years for Mars and about 350 years for Earth, so the Chandler wobble could also be excited by internal processes, like planetary quakes or flows in the liquid core. Measuring the Chandler wobble on different planets therefore provides not only knowledge about the forcing processes and material properties, but also insights into comparative planetology."

Whatever the cause, the wobble is providing fresh insights into the interior of Mars, notably its material properties and thermal state. By assessing the amount of time it takes for the pole to complete a wobble cycle, scientists learn the extent to which the Red Planet's mantle can deform.

"The deformations of the Martian mantle mainly depend on its rigidity, and the rigidity is strongly dependent on temperature," Attilio Rivoldini, a physicist at the Royal Observatory of Belgium, tells All About Space.

"By measuring the Chandler wobble period, we can deduce information about the thermal state because we have a good knowledge about the rigidity of candidate Mars mantle materials. This knowledge has mainly been acquired by studying the composition of

> "THE DEFORMATIONS OF THE MANTLE DEPEND ON RIGIDITY, AND THE RIGIDITY IS STRONGLY DEPENDENT ON TEMPERATURE" ATTILIO RIVOLDINI


© NASA

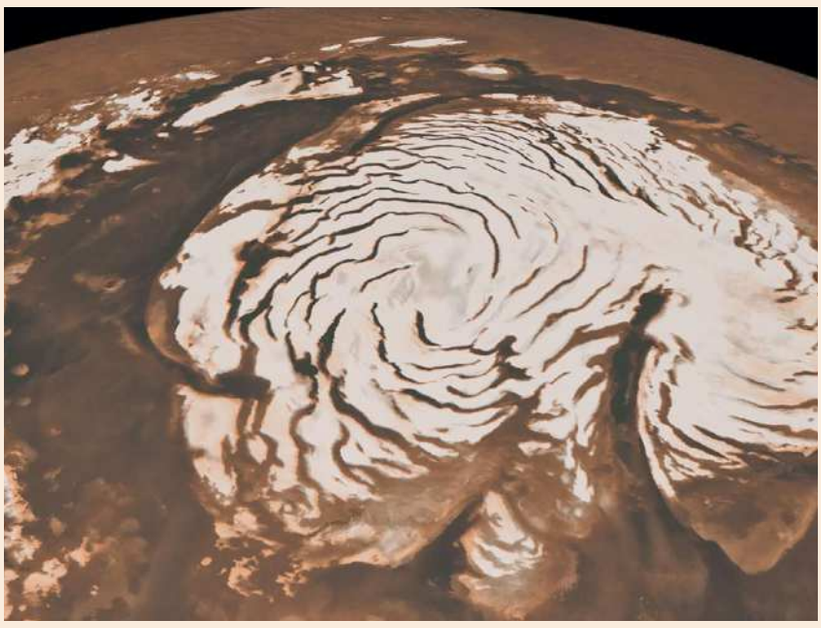
Martian meteorites and by performing laboratory experiments about the material properties of candidate materials."

The wobbling of Mars has certainly piqued the interest of scientists, and further studies are sure to be carried out over the years. New knowledge about the planet's temperature and composition is vital in gaining a better picture of the planet, and Dehant is among those at the forefront of future missions.

"I think the next study of interest will be the measurement of the Mars nutation from the InSight mission," says Dehant. "Nutations are periodic changes in the orientation of the planet, mainly due to the gravitational interaction with the Sun, and the amplitude of the nutations depends on a well-known forcing and on the interior structure of Mars, in particular on the liquid core." Ongoing measurements of the rotation of Mars using the RISE experiment on InSight – the robotic lander studying the Red Planet's deep interior which launched in 2018 – is already proving exciting, and could lead to many breakthroughs.

"By comparing the measured nutation with the external forcing, the core radius can be determined, and constraints on the chemical composition of the core be deduced," Dehant adds. "Unlike the Chandler wobble, a resonant amplification can only occur if Mars has a liquid core. By measuring the Chandler wobble and the nutations, complementary knowledge about the interior structure of Mars can be obtained." Scientists are sure to be shaking with excitement at what could be unearthed.

DAVID CROOKES
Science and technology journalist
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.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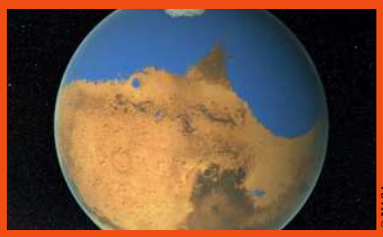
Left: Polar motion has not been detected for any other Solar System body other than Mars and Earth

THE THEORIES

What could be keeping the Chandler wobble going on Mars?

1 Past evidence of surface water

On Earth, the Chandler wobble is excited, in part, by pressure at the bottom of the ocean, but Mars does not have surface water today. It lost flowing liquid billions of years ago, but it was once awash with water in the form of lakes and oceans. Could that have aided the wobbly rotation? As it stands, it would require much further study.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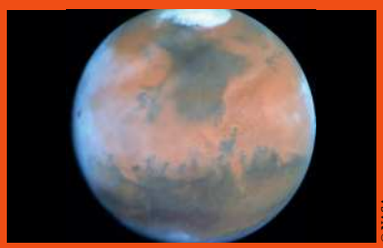
2 Internal issues

Researchers have considered whether the excitations are produced by core-mantle interactions or marsquakes. Neither can be excluded at this stage, but the scientists believe them to be unlikely. Past research has already suggested that marsquakes are too small to excite polar motion to an observable level.


© NASA

3 Seasonal atmospheric pressure changes

Mars has two ice caps – north and south – that are made of frozen water. Over each pole's respective winter, this is accompanied by a layer of frozen carbon dioxide, which melts and reforms seasonally. The atmospheric pressure changes related to the seasonal mass exchange between the two caps are thought to be the principal mechanism behind the ongoing Chandler wobble.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IS LIFE FROM MARS?

COULD WE ALL BE MARTIANS? WE PUT THE THEORY THAT LIFE ON EARTH IS OF EXTRATERRESTRIAL ORIGIN UNDER THE MICROSCOPE

Words Jonathan O'Callaghan

Around 4 billion years ago the chemical constituents of life stewed in a primordial soup on Earth. Gradually, over time, this formed primitive single-celled microbial life, which later evolved into multi-cellular life. Over the next few billion years this life gradually evolved into the species that inhabit the Earth today, from plankton to people. Those first ingredients of life formed on Earth itself, with no external input.

That's the widely accepted theory as to how life on Earth began, but not all are convinced. Some are sure that life on Earth began elsewhere, being transferred to Earth by comets or asteroids, where it gained a foothold and evolved into modern life forms. One theory that has risen to the fore in the last few years is that this life originated on Mars, and it's given credence by the discovery made by NASA's Curiosity rover that the Red Planet was almost certainly wet, and possibly habitable, long ago in its distant past.

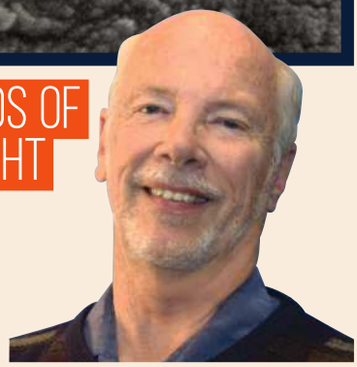
It's a theory that has been met with harsh criticism at worst, and mild trepidation at best. 'Extraordinary claims require extraordinary evidence,' is an oft-quoted retort to such outlandish theories, but some scientists are convinced that such extraordinary evidence is not beyond our reach.

One of the main proponents for life originating on Mars is Professor Steven Benner of the Westheimer Institute of Science and Technology in Gainesville, Florida, USA. Presented at the Goldschmidt Meeting in Florence, Italy earlier this year, Benner described how the early conditions on Mars might have been more suited to the building blocks of life than the young Earth.

Life as we know it requires three crucial ingredients, namely RNA, DNA and proteins. RNA, or ribonucleic acid, forms through a difficult process of 'templating' atoms on the crystalline surface of minerals. The minerals required for this templating to occur would likely have dissolved in the seas of the young Earth if it was covered in a global ocean, as has been suggested, but they could have more easily existed on a drier Mars according to Benner. "I would certainly give my odds of life originating on Mars as right now about 50:50," explains biochemist Dr David Deamer of the University of California, Santa Cruz, USA. "I think Mars, at one point, based on recent observations, had the kind of conditions that would allow simple replicating systems to appear. The question of whether these then were delivered to Earth is much more problematic, and it's a possibility although I don't think necessarily a plausibility."

The ALH84001 meteorite, which some scientists say carried evidence of life from Mars

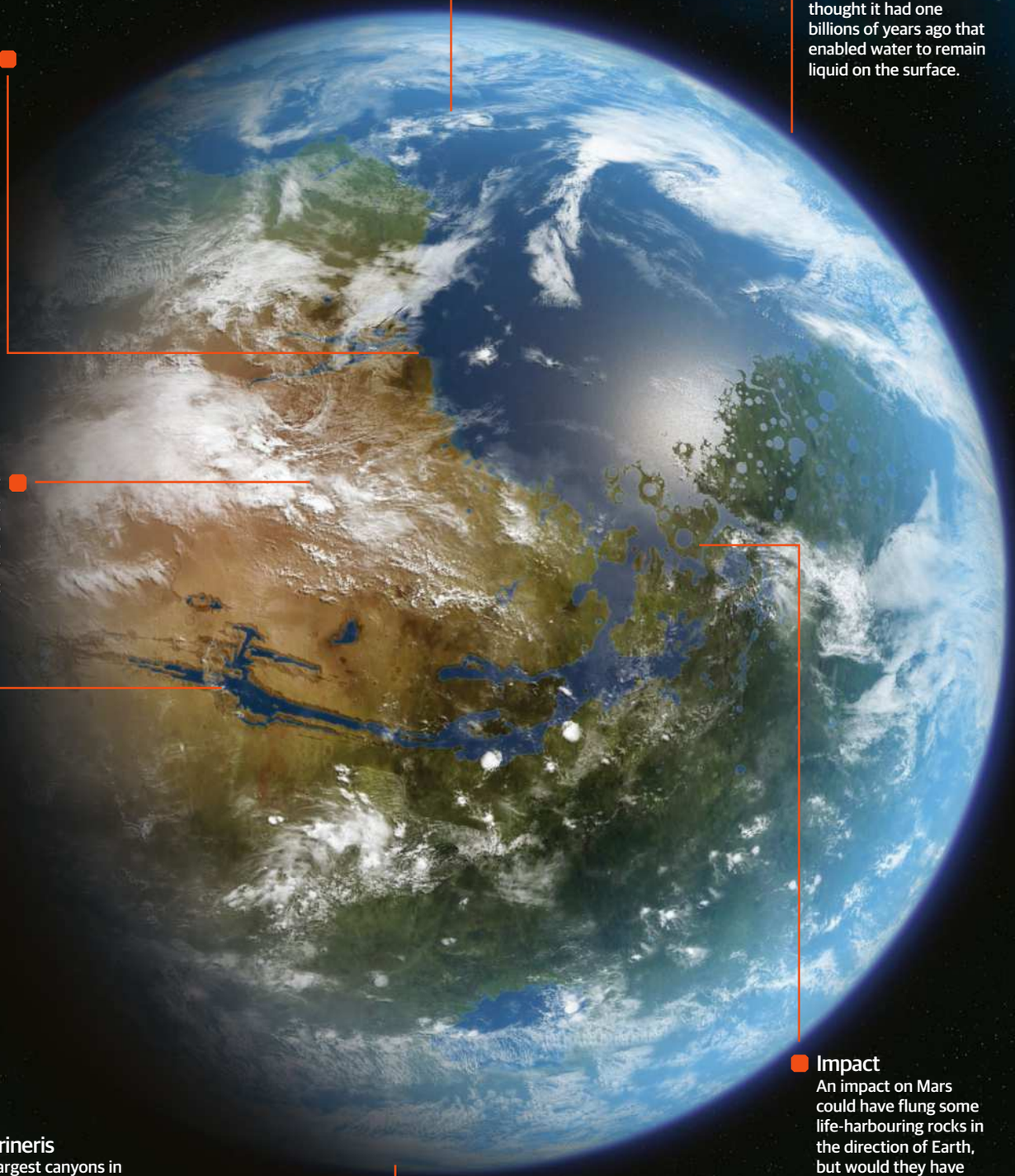
"I WOULD CERTAINLY GIVE MY ODDS OF LIFE ORIGINATING ON MARS AS RIGHT NOW ABOUT 50:50" DR DAVID DEAMER



Benner's research is based around the assumption that Earth was once wholly covered in water. This might sound conducive for life but, in fact, it is quite the opposite. Life is dependent upon polymerisation chemistry, which is the process through which simple monomer molecules are reacted together to form complex polymers. In basic terms, life forms through the bonding of simple molecules,

NASA's Curiosity rover found evidence of an ancient streambed on Mars, supporting the postulation that the Red Planet was once wet and habitable

IS THIS WHAT MARS ONCE LOOKED LIKE?



Northern hemisphere
The northern hemisphere of Mars is at a much lower elevation than the southern hemisphere, leading some scientists to speculate it was once the location for a huge ocean.

Atmosphere
Mars has since lost its atmosphere, but it's thought it had one billions of years ago that enabled water to remain liquid on the surface.

Wet and dry
Life would have more easily formed at the boundary of water and land where it could have gone through the wetting and drying process needed to evolve.

Volcanic activity
Research suggests that many of the land masses at higher elevation we can see on Mars today were formed by volcanic activity in its past.

Impact
An impact on Mars could have flung some life-harbouring rocks in the direction of Earth, but would they have survived the journey?

Valles Marineris
One of the largest canyons in the Solar System, it is thought that at least part of Valles Marineris was formed by flowing water.

Poles
Evidence for water on Mars remains at the poles, where large quantities of ice are still present in the modern day.

5 REASONS LIFE MIGHT HAVE COME FROM MARS...

1 Earth was too wet

If Earth was indeed once covered in a global ocean, it would not have been able to support the constituents of life as they would probably also require dry land.

2 Mars was once habitable

Evidence suggests that Mars not only had water in its past but also a thicker atmosphere, which would have enabled life to form on its surface.

3 Rare bacteria

Some rare forms of bacteria have magnetite that can be used as a biological compass to follow the magnetic field of Earth. They may also be found in the Martian Allan Hills meteorite.

4 Meteorites reach Earth

We know that meteorites (some from Mars) regularly make it to Earth, even in the modern day and much more so in the past. Could one of these have brought the ingredients for life?

5 Volcanic activity

Mars is thought to have been volcanic in the past, which would have provided land upon which primitive life could form.

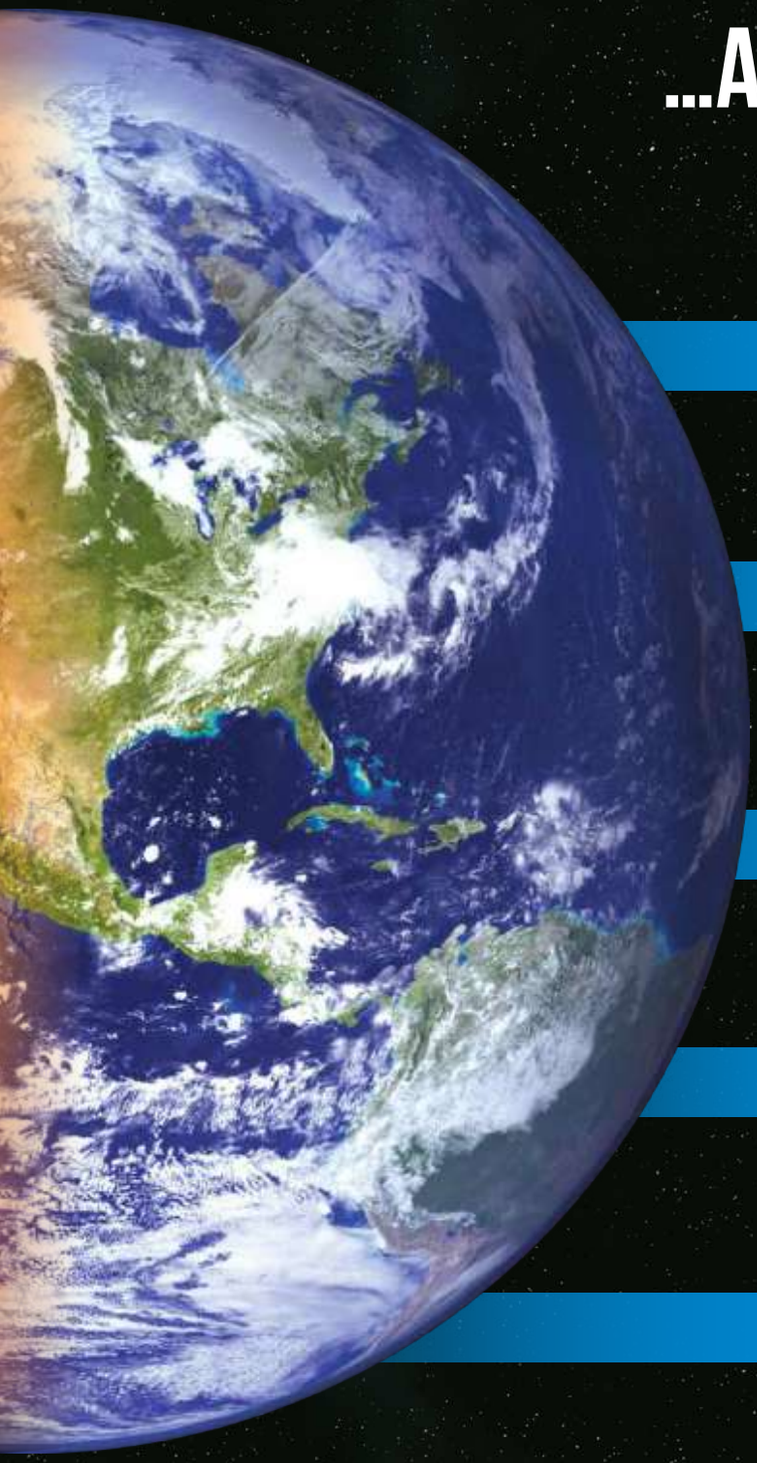
such as amino acids and nucleotides, into more complex polymers such as proteins and nucleic acids respectively.

For this to happen, however, water molecules need to be pulled from between monomers. If Earth really was once covered in a global ocean, as Benner suggests, then this would have been incredibly unlikely to occur. For monomers to form polymers, there needs to be a wetting and drying environment, something a completely wet Earth could not provide. Benner says that while Earth was covered in a global ocean, Mars was not. The Red Planet instead only had shallow oceans where the minerals essential for the origin of life would have been more likely to occur. Dr Deamer, however, isn't so convinced by this aspect of the theory.

Our observations of Mars heavily suggest that it would have had volcanic activity that would have caused land to rise up from the oceans, producing large land masses on the Red Planet where life could form. Benner's assumption is that this same volcanic activity did not occur on Earth 4 billion years ago. "My disagreement arises from his assumption that Earth was

"MANY METEORITES FROM MARS HAVE LANDED ON EARTH, HAVING UNDERTAKEN JOURNEYS OF MILLIONS OR BILLIONS OF YEARS"

...AND 5 REASONS IT MIGHT HAVE BEGUN ON EARTH



1 Life could have formed here

Most evidence suggests that Earth had a volcanic beginning just like Mars, which means it would have had land masses upon which life could form.

2 It was habitable

Unlike Mars we know for certain that Earth was and still is habitable as we're still here and there's evidence for life stretching back to the earliest of days.

3 The distances are extreme

Life travelling from Mars on an asteroid to Earth would have to make a daunting journey of 225 million kilometres (140 million miles), which leads us to...

4 Harmful radiation

The journey from Mars to Earth is fraught with peril, not least from the huge amounts of radiation that would kill any unprotected life attempting to migrate.

5 We're yet to find extraterrestrial life

Theories of life existing elsewhere, let alone originating there, are pure conjecture. So far there is only one world in the universe we know to have life, and that is Earth.

covered by a global ocean," says Dr Deamer. "Mars had volcanic activity without a doubt, but I don't see any reason why those same volcanic activities would not have occurred on Earth and that volcanoes would have arisen out of the early ocean." Evidence for this occurring on Earth is apparent due to islands such as Hawaii and Iceland, so Dr Deamer suggests "it's likely that we had volcanic activity producing land masses above the global ocean, and this was likely the case on Mars as well."

If this was the case, there's no reason that life could not have begun on Earth. In fact, Dr Deamer and his team are currently in the process of finalising some groundbreaking research into producing life akin to what might have been on Earth 4 billion years ago. "We're now at the point where we can put together in the laboratory systems of molecules that have some of the properties of a primitive form of life," explains Dr Deamer. "We haven't got that to reproduce yet, but I can see looking just a few years in the future that the progress is such that we will have a laboratory demonstration of a replicating chemical system that has the properties of life." Benner's theory continues that, assuming life did begin on Mars and not Earth, there is then the issue of how this life was transported to our planet. How did it get here? Many meteorites from Mars have landed on Earth, having undertaken journeys of millions or perhaps billions of years, and it is on these meteorites that Benner suggests life could have been transported.

One such meteorite, known as Allan Hills (ALH) 84001, is a popular piece of evidence favoured by proponents of the 'life from Mars' theory. The meteorite, which was discovered in Allan Hills, Antarctica in late December 1984,

In January 2013, scientists on NASA's Astrobiology Icy Worlds team ran experiments to see if organic molecules could be brewed in a simulated ocean like that found on the young Earth

was thought by some to contain microscopic fossils of Martian bacteria. The presence of this fossilised bacteria, however, is the cause of much contention. If true, it would confirm that life really could have begun on Mars and, perhaps, the ingredients for life on Earth could have been transported by an asteroid. The theory is that ALH 84001 was blasted from the surface of Mars around 4 billion years ago before making its journey of 225 million kilometres (140 million miles) to Earth.

"The main deal [with ALH 84001] was that things looked like they might be fossils," says Dr Deamer, "and that was done using a scanning electron microscope and, sure enough, there's stuff that looks like it might be fossilised bacteria. However, there are a bunch of minerals that can also look similar to that, and if you're going to make an extraordinary claim like 'this is a fossil', you must have extraordinary supporting evidence. When people looked at all that evidence critically they were not convinced. It was not sufficient to get the jury of peers who are critical and sceptical scientists to agree."

"WHILE TRUE PANSPERMIA MIGHT SEEM A BIT FAR FETCHED, THE POSSIBILITY OF LIFE ORIGINATING ON MARS IS ONE THAT CERTAINLY MERITS FURTHER INVESTIGATION"

Another problem with the suggestion that life was carried to Earth on an asteroid is the enormous distances mentioned earlier. Space is a harsh environment; outside the protective magnetosphere of Earth, radiation from the Sun and outside the Solar System is deadly to almost all forms of life. Some meteorites are thought to have taken hundreds of millions or billions of years to reach Earth, and for any form of life to survive that long on an asteroid seems somewhat implausible. Some suggestions that life could reside inside such space rocks is also unlikely, as the relatively small size of asteroids would be unlikely to provide sufficient protection from harmful radiation.

This is where another theory of life on Earth being of extraterrestrial origin, true panspermia, has been met with unreserved scepticism. True panspermia is the theory that life did not originate on Earth, but nor did it originate on Mars; proponents of this theory suggest that life began elsewhere in our galaxy, perhaps in another planetary system, before being transferred here.

One proponent of this theory is the somewhat controversial astronomer Chandra Wickramasinghe, professor and director of the

Buckingham Centre for Astrobiology at the University of Buckingham, UK, whose theories of true panspermia, which he formed alongside the late astronomer Sir Fred Hoyle, have been met with a critical reception.

"The total [number of exoplanets] has been reckoned by some NASA scientists at 144 billion Earth-like planets in our Milky Way alone," explains Wickramasinghe. "If you accept that estimate then the nearest Earth-like planet to us is only three or four light years away, which is sort of spitting distance in cosmic terms. So the position I have maintained is that life on Earth is most unlikely to have originated on Earth."

Wickramasinghe's view of true panspermia is that all life began at a similar time at the dawn of the universe, spreading between the planets and stars in the process. It's a contentious theory to say the least; there's not a lot of evidence to support it. "The whole process of the origin of life occurred maybe very early in the history of the universe, maybe in the first 100 million years after the Big Bang," he says. "This was when the universe was compact, much smaller than it is now, and communication between one planetary system and another was more intimate. I think life began not in a puddle on Earth, but in the totality of a planetary puddle that existed at the dawn of the universe. There's no way that life can be confined to one place, is my conclusion."

Dr Deamer, however, was quick to point out a key problem with true panspermia. "If you look at the distances involved in true panspermia, things getting to us from other solar systems in our galaxy, the mathematics make it virtually inconceivable that anything could travel those distances and stand up to cosmic radiation long enough to make it to Earth," he explains. "So you've really got to look at the maths and the physics of what would be required to get something even from the nearest star about four light years away travelling at way below light velocity to get here. These things would take billions of years to get here and they'd be exposed to all kinds of ionising radiation in the interim, so it just seems highly implausible that panspermia is going to stand up to that kind of critical analysis."

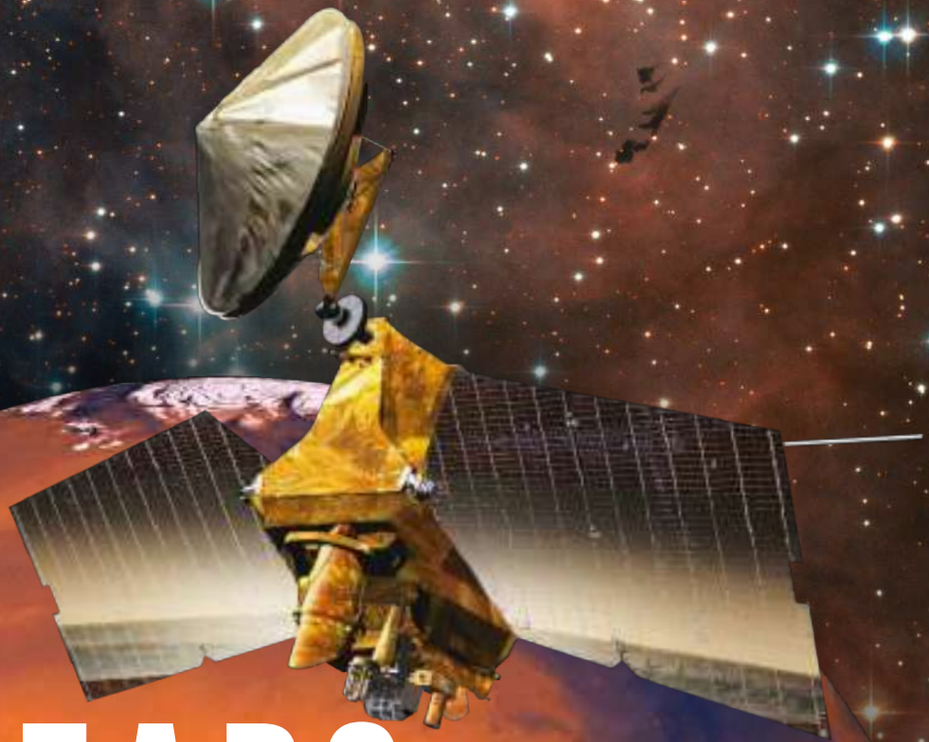
While true panspermia might seem a bit far-fetched for now, the possibility of life originating on Mars is one that certainly merits further investigation. As is the case with theories of this sort, however, the philosophical theory of Occam's razor often holds true: the simplest answer, in this case that life began on Earth, is normally correct.

"We do know that pieces of Mars get to Earth, we do know that organic compounds were probably on Mars and we do know that [those compounds] could come in a Martian meteorite," surmises Dr Deamer. "In scientific judgement it's still at a level of being implausible, but it's less implausible than true panspermia."

So, are we actually Martians? Is the Red Planet the source of the building blocks that became life on Earth? It'll take some extraordinary evidence to prove, but maybe, just maybe, that evidence is waiting to be found...

Could it have held life? Martian soil under the microscope of the Opportunity rover. The larger rocks are about the size of sunflower seeds

© Jay Wong; NASA/JPL Caltech; Daein Bollard



OVER 10 YEARS AROUND MARS

OVER A DECADE AGO, NASA'S MARS RECONNAISSANCE ORBITER (MRO) ARRIVED AT THE RED PLANET. WE TAKE A LOOK AT ITS BIGGEST DISCOVERIES

Words Giles Sparrow

MISSION OBJECTIVES

- Understand the present climate of Mars
- Work out the nature of the complex Martian terrain
- Search for evidence of aqueous and hydrothermal activity
- Identify landing sites for future Mars missions
- Return data from craft on the surface during relay phase

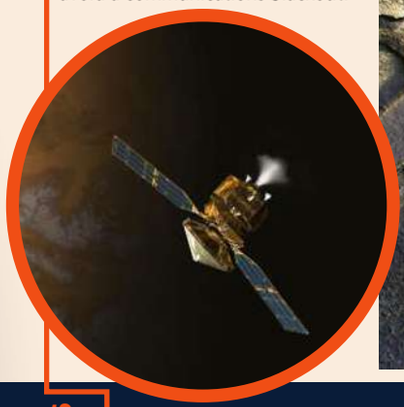
OVER 10 YEARS AROUND MARS

10 March 2006

Arrival at Mars

The MRO arrives in Martian orbit, initially entering a highly elliptical orbit over the planet's poles. After initial checks, MRO begins an aerobraking manoeuvre that takes five months to complete, taking advantage of the natural brake provided by friction with the atmosphere to save thruster fuel.

By the time the process is complete in early September, MRO's 112-minute orbit around Mars ranges between 250 to 316 kilometres (155 to 196 miles) above the surface. The science operations are postponed until November to avoid a communications blackout.



13 December 2006

Targeting a layered canyon

After months of aerobraking and instrument testing, one of the first targets for MRO's High Resolution Imaging Science Experiment (HiRISE) camera is an area close to the Martian north pole. Here, frozen carbon dioxide (dry ice) is laid down by winter frosts, carrying with them dust from the atmosphere.

As the upper layers of frost evaporate in spring, they leave dust behind, slowly building up a distinctive and complex layered terrain, whose inner structure is exposed around the edges of the canyons and craters.

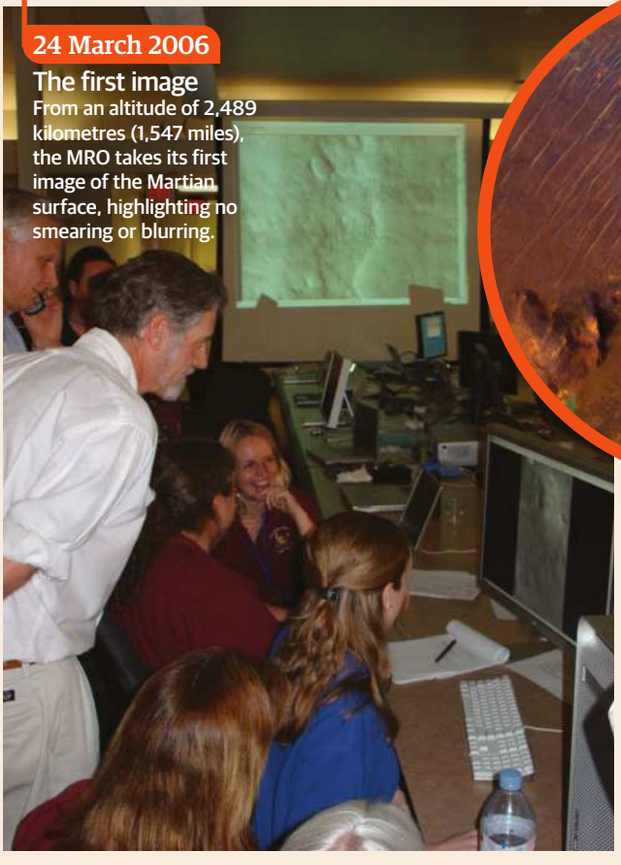
7 November 2007

Weather watch

The Mars Color Imager (MARCI) delivers wide-angle, lower-resolution images of the surface, allowing MRO to produce daily weather maps for the planet. In late 2007, MARCI captures a developing dust storm (red clouds) on the edge of the retreating north polar ice cap in Utopia Planitia.

Northern-hemisphere storms tend to remain local (this one covers 500 kilometres (310 miles) and lasts 24 hours), but those in the southern-hemisphere summer can envelope large swathes of the planet and last for weeks or even months.

2006 2007 2008



24 March 2006

The first image

From an altitude of 2,489 kilometres (1,547 miles), the MRO takes its first image of the Martian surface, highlighting no smearing or blurring.

24 March 2007

MRO captures the Nili Fossae region

This enhanced colour image, taken by the HiRISE camera in March 2007, shows an area of the Nili Fossae region. The image is part of a series of experiments to examine more than two dozen possible landing sites for NASA's Curiosity rover.

19 February 2008

Capturing an avalanche

When MRO revisits the layered terrain at the north polar cap in the Martian spring, scientists hope to study the way in which carbon dioxide frosts evaporate from underlying sand dunes.

It comes as something of a surprise, however, when an image from HiRISE ends up capturing no fewer than four separate avalanches thundering down a layered cliff face more than 700 metres (2,296 feet) tall. Further observations confirm that similar avalanches recur in Martian spring – they are probably triggered when blocks of dust-laden dry ice collapse as frozen carbon dioxide slowly thaws.

27 February 2008

MRO captures sand dunes defrosting

27 May 2008

Flight of the Phoenix

Throughout its time of operation at Mars, the MRO has been used in conjunction with several other spacecraft, helping to identify potentially interesting landing sites for rovers, making observations to supplement those from other orbiters, and tracking other missions once they have reached the surface.

In 2008, MRO uses its HiRISE to capture one such mission on its final descent to the Martian surface. The Phoenix Lander is shown here at an altitude of about 13 kilometres (eight miles), shortly after its parachute opens.

4 February 2009

Spiders from Mars

One of MRO's most spectacular discoveries are the curious, organic-looking patterns that develop in spring at the edge of the south polar cap. With a resemblance to trees or spiders, these dark patterns – also known as starbursts – form dark tendrils that spread out across the bright, frost-covered terrain.

It is thought they are formed by sublimation – the direct transition of frozen carbon dioxide ice into gas. This happens in pockets beneath the surface and gas finds its way to weak points or fissures where it can break out, often carrying dust with it that falls back to the surface. This dust darkens the ice cap, so it absorbs more sunlight and heats up, which continues the cycle.

2008

2009

23 March 2008

Phobos flyby

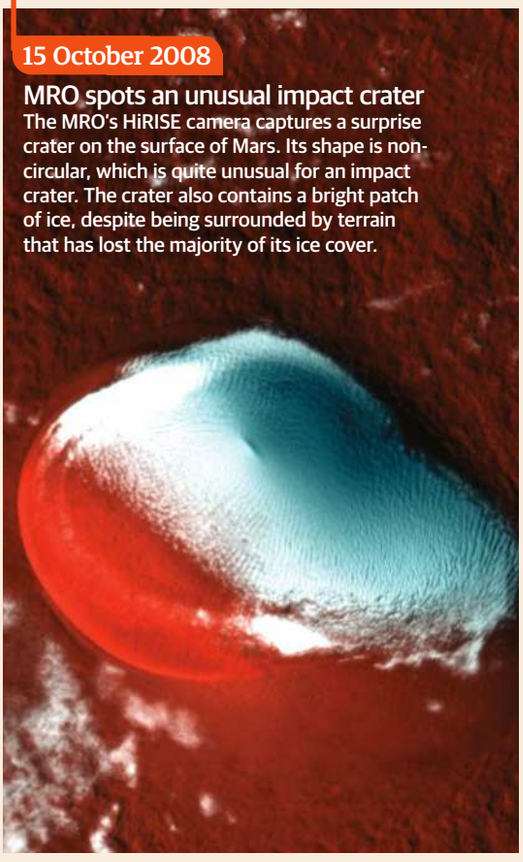
The MRO team turn the HiRISE camera away from Mars to image its two satellites, Phobos and Deimos, at the highest resolution yet obtained. The larger of the two moons, Phobos, orbits closer to Mars, circling the planet once every seven hours and 40 minutes.

Seen in this image from 6,800 kilometres (4,200 miles), the potato-shaped moon's most prominent feature is a crater called Stickney. The curious grooves that appear to radiate from the crater and run parallel with the moon's longer axis are thought to be stress fractures, caused as Martian tidal forces push and pull on the satellite.

15 October 2008

MRO spots an unusual impact crater

The MRO's HiRISE camera captures a surprise crater on the surface of Mars. Its shape is non-circular, which is quite unusual for an impact crater. The crater also contains a bright patch of ice, despite being surrounded by terrain that has lost the majority of its ice cover.

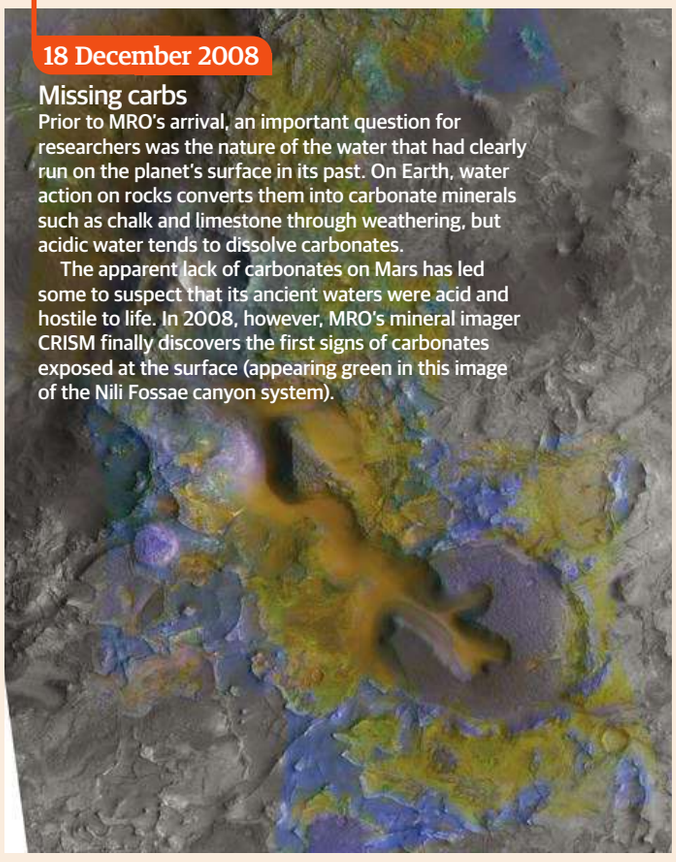


18 December 2008

Missing carbs

Prior to MRO's arrival, an important question for researchers was the nature of the water that had clearly run on the planet's surface in its past. On Earth, water action on rocks converts them into carbonate minerals such as chalk and limestone through weathering, but acidic water tends to dissolve carbonates.

The apparent lack of carbonates on Mars has led some to suspect that its ancient waters were acid and hostile to life. In 2008, however, MRO's mineral imager CRISM finally discovers the first signs of carbonates exposed at the surface (appearing green in this image of the Nili Fossae canyon system).



OVER 10 YEARS AROUND MARS

21 February 2009

Martian Moon Deimos in high resolution

The smaller of Mars' moons, Deimos, is captured by the HiRISE camera onboard the MRO in February 2009. The moon is around 12 kilometres (7.5 miles) across and has a smooth surface, apart from dents created by the most recent impact craters.

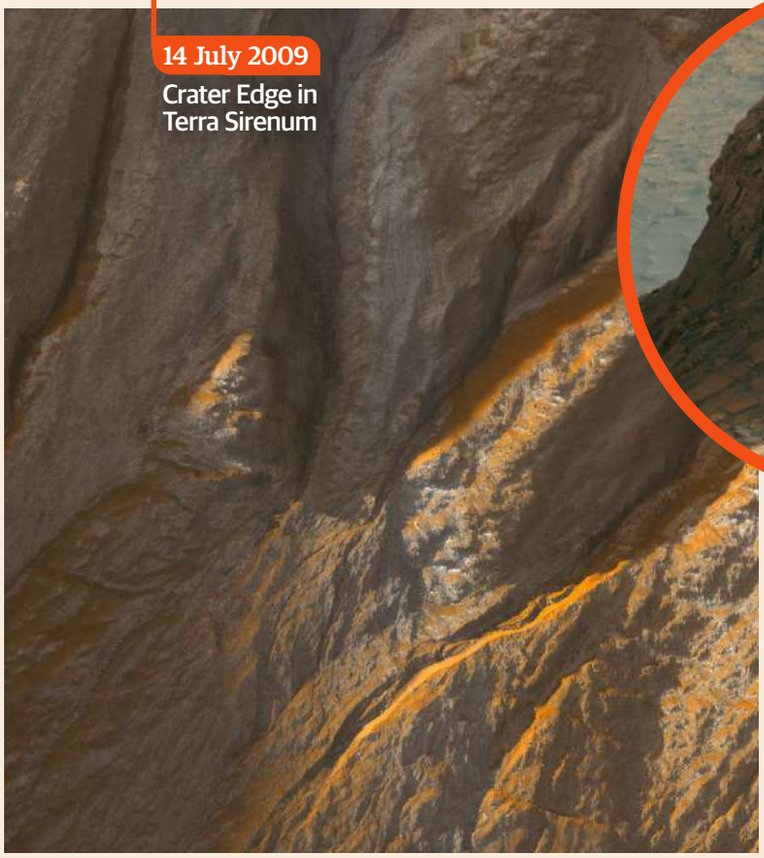
14 July 2009

Snapping Victoria Crater at Meridiani Planum

2010

14 July 2009

Crater Edge in Terra Sirenum



14 July 2009

View of Cape Verde from Cape St. Mary in mid-afternoon, in false colour

2 March 2010

Low-latitude ice

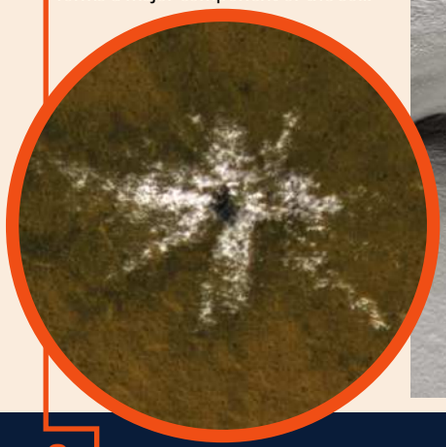
MRO's Shallow Subsurface Radar Instrument (SHARAD) emits radar beams that penetrate the upper layers of the surface and send back reflections whose characteristics are altered by the electrical properties of the soil beneath. The presence of water makes the Martian sands electrically conductive and results in a particularly strong signal.

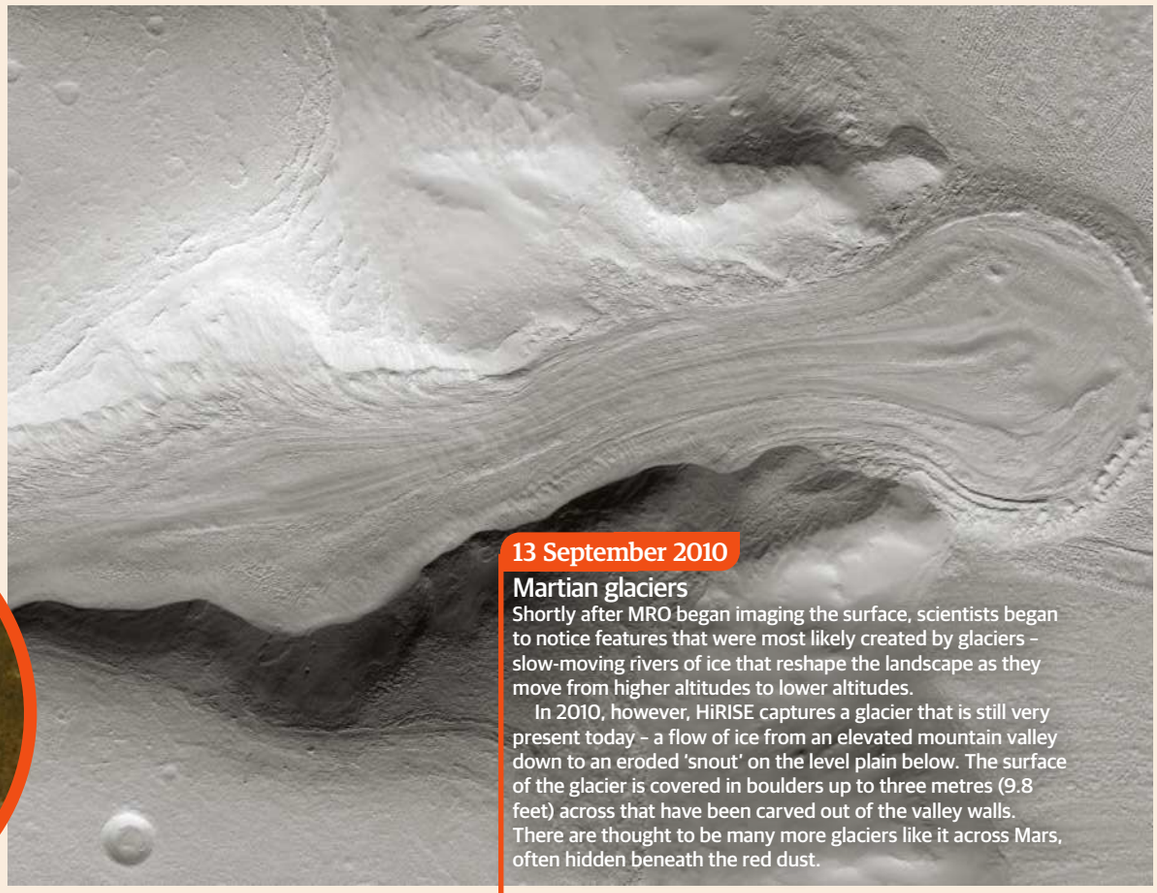
In this image from 2010, yellow streaks represent individual radar tracks across the Deuteronilus Mensae region, and blue indicates the location of water ice detected by SHARAD. Deuteronilus Mensae is a region of collapsed canyonlands in the middle latitudes of the northern hemisphere – the ice seems to be buried below a thin layer of surface dust and rocks.

19 May 2010

Craters of ice

The 'Red Planet' owes its nickname to the rusty Martian sands that cover its surface – but this HiRISE image in May 2010 reveals just how thin that surface layer really is. A small ten-metre (32.8-foot) crater formed here after the area was last photographed in March 2008, and has pierced straight through the red soil to hit an underlying layer of ice, blasting snowy 'ejecta' across the surrounding terrain (colours have been processed to highlight the contrast). The crater is at mid-northern latitudes, where MRO observations suggest ice forms a major component of the soil.





13 September 2010

Martian glaciers

Shortly after MRO began imaging the surface, scientists began to notice features that were most likely created by glaciers – slow-moving rivers of ice that reshape the landscape as they move from higher altitudes to lower altitudes.

In 2010, however, HiRISE captures a glacier that is still very present today – a flow of ice from an elevated mountain valley down to an eroded 'snout' on the level plain below. The surface of the glacier is covered in boulders up to three metres (9.8 feet) across that have been carved out of the valley walls. There are thought to be many more glaciers like it across Mars, often hidden beneath the red dust.

2010

2011

25 June 2010

Mars' wet north

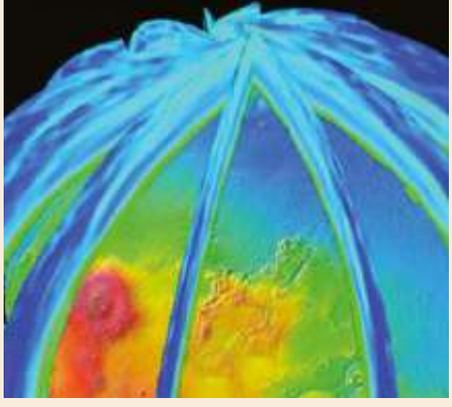
Ancient hydrated minerals had already been found in the southern highlands but the northern plains seemed to have a disappointingly dry history. Using the CRISM spectrometer, researchers target several craters and identify multiple signatures from hydrated, clay-like minerals (such as those shown here at Lyot Crater). The crater seems to have punctured through the overlying dry soil to expose an ancient layer below, revealing evidence that watery and hospitable conditions were once global, perhaps 4 billion years ago.

20 August 2010

Mapping the atmosphere

MRO's Mars Climate Sounder (MCS) studies the atmosphere by viewing sections through air above the horizon at a variety of wavelengths.

This MCS image shows curtain-like profiles of the atmosphere above the northern hemisphere, based on 13 orbits' worth of observations. Colour coding indicates different temperatures in the atmosphere ranging from -70°C (-94°F) in green, to a chilling -150°C (-238°F) in purple. MCS can also detect water ice clouds, accumulations of water vapour and dust storms.



3 February 2011

Changing dunes

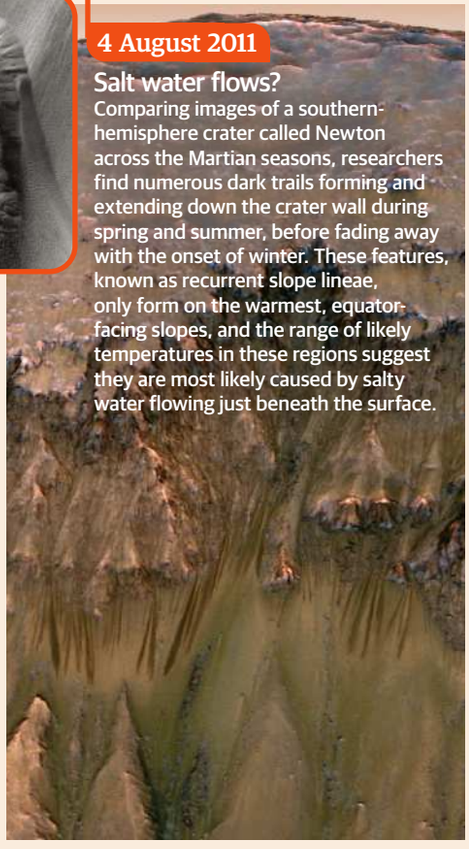
The vast dune sea known as the Vastitas Borealis surrounds the Martian north pole just beneath the polar cap, and was long assumed to be in a state of permanent deep-freeze.

However, this set of HiRISE images showing the area across two Martian years (roughly four Earth years) shows substantial erosion has taken place around the rim of a steep-edged dune. The changes are partially due to the seasonal accumulation and evaporation of carbon dioxide frost from the atmosphere, but are also affected by strong winds that shift the Martian sands and quickly wipe away signs of previous landslips.

4 August 2011

Salt water flows?

Comparing images of a southern-hemisphere crater called Newton across the Martian seasons, researchers find numerous dark trails forming and extending down the crater wall during spring and summer, before fading away with the onset of winter. These features, known as recurrent slope lineae, only form on the warmest, equator-facing slopes, and the range of likely temperatures in these regions suggest they are most likely caused by salty water flowing just beneath the surface.



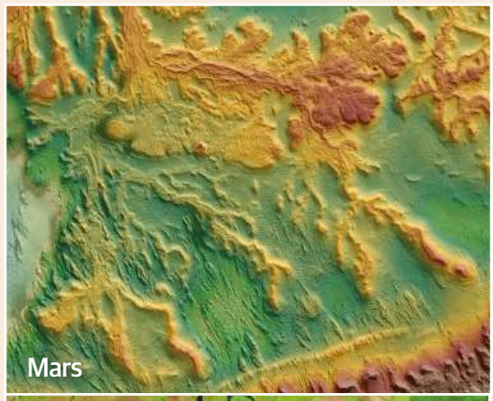
1 April 2012

Martian dunes covered in frost

6 September 2012

Tracking Curiosity

Prior to the arrival of NASA's Curiosity rover on Mars in 2012, MRO plays a key role in gathering data about its landing site in Gale Crater. As with Phoenix in 2008, the HiRISE camera tracks the probe during its descent, and it has been used to monitor the rover's progress intermittently throughout the rest of Curiosity's mission. The spacecraft's rockets blow away the red surface dust during the "sky crane" descent stage to the Martian surface, revealing the darker iron-rich rock beneath, which can be seen in the centre of the photograph.



16 July 2013

A coastal delta?

Scientists have long speculated that the northern plains were once covered in a shallow ocean. In 2013, using HiRISE images of the Aeolis Dorsa region (which sits between the northern and southern hemisphere), researchers create an elevation map and find a series of inverted ridges fanning out as they run downhill – a structure similar to how river deltas flow into Earth's seas. It's the strongest evidence yet that the ocean theory is correct.

2012

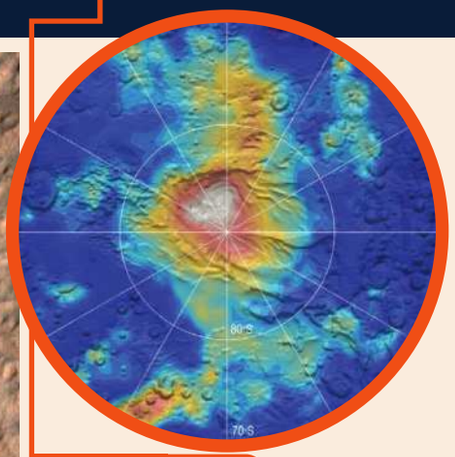
2013

16 February 2012

Twister on the move

The existence of dust devils on the Martian surface had been suspected since the 1970s, but MRO surprises everyone by delivering stunning images of these tornado-like whirlwinds in action. This relatively small-scale dust devil is about 30-metres (98-foot) wide and 800-metres (2,624-foot) high – others can grow much larger.

Dust devils scour the Martian surface clear of dust, frequently leaving scribble-like dark trails where they expose the underlying bedrock. They are thought to form in the same way as Earth's dust devils, when a pocket of warm air is trapped at the surface by overlying cold air and is then finally allowed to rise, creating a spinning updraft.



11 September 2012

Winter wonderland

During the southern-hemisphere winter of 2006 to 2007, the MRO uses its Mars Climate Sounder to study cloud formations over the south polar ice cap.

In 2012, a team of scientists announce a new analysis of this data, confirming the presence of a huge carbon dioxide snow cloud, some 500 kilometres (310 miles) across, hovering over the south pole. The cloud, made of frozen "dry ice" crystals, would deposit snow on the ground in the right conditions, perhaps explaining how the south pole grows from a small residual ice cap that persists through summer, to an extensive snowcap covering a large amount of the southern hemisphere.

8 November 2013

Dunes on the rim of an impact basin

This sand dune is known as a barchan, which forms when the wind blows in one direction for long periods of time, causing it to slowly creep across the surface of Mars. This particular dune is located on the western rim of the Hellas impact basin, in the southern hemisphere of the Red Planet.

26 February 2014

Icy revelations

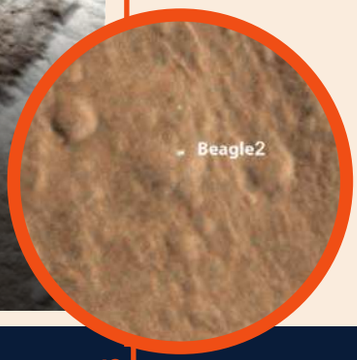
MRO's high-resolution cameras have discovered many unsuspected features on Mars, including unusual terraced craters like this one. At first glance, its bulls eye structure makes it look as though a second meteorite has struck the exact centre of an earlier crater, but the reality is rather different.

Terraced craters form when an impact penetrates through layers of material that have different strengths – in this case, a relatively weak sheet of ice just below the surface has been hollowed out to form the crater's wide outer walls, while the much tougher rock beneath has only been excavated at the point of impact itself.

16 January 2015

The spacecraft locates the Beagle 2 lander

Beagle 2, a lander released by the Mars Express Orbiter on Christmas Day in 2003, is uncovered by MRO with its solar arrays partially deployed on the surface of Mars.



17 May 2015

MRO snaps a "Hollywood movie site"

Using the HiRISE camera, the Mars Reconnaissance Orbiter snaps the region Acidalia Planitia, which is featured in the best-selling novel and movie, *The Martian*.

2013 2014 2015

19 November 2013

Spotting a recent impact

The MRO's continuous watch over Mars gives us the ability to see the rate of changes to the planet's surface. This goes not just for seasonal processes such as the cycle of the polar caps, or the eruption of dust storms, but also for external factors such as impact cratering.

This spectacular crater, which is 30 metres (98 feet) across but surrounded by an extensive pattern of impact debris, or 'ejecta', formed after July 2010 and before May 2012, between two imaging passes of MRO's Context Camera. This more detailed false-colour image from the HiRISE camera uses blue to show where reddish surface dust has been blasted away.

19 October 2014

Watching a comet flyby

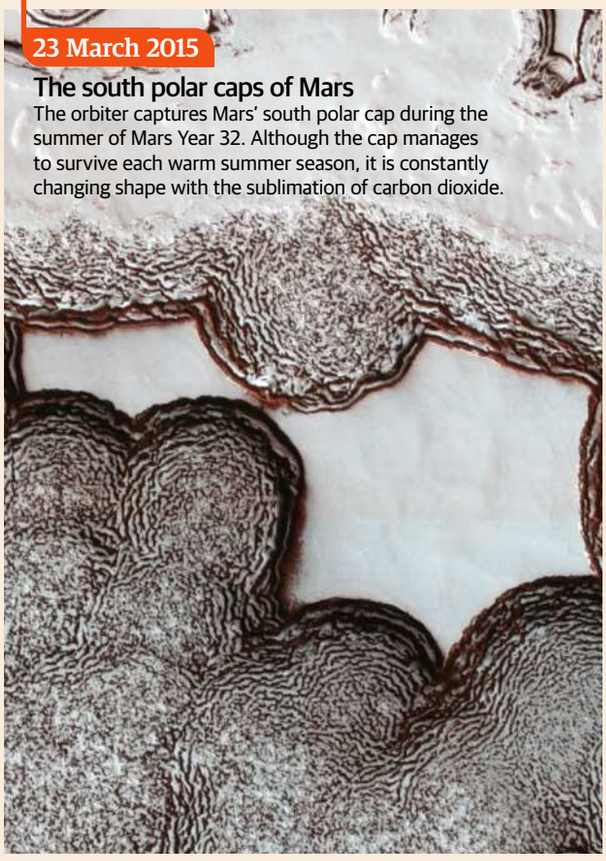
In late 2014, space agencies take precautions with MRO and their other Mars orbiters as the recently discovered Comet Siding Spring makes an unusually close approach to the Red Planet.

When the comet was first discovered, it was thought to be on a possible collision course with Mars – with the potential to create a new crater several kilometres or miles across. In the end, however, Siding Spring passes within 140,000 kilometres (86,992 miles) of Mars – about one-third of the distance from the Earth to the Moon.

23 March 2015

The south polar caps of Mars

The orbiter captures Mars' south polar cap during the summer of Mars Year 32. Although the cap manages to survive each warm summer season, it is constantly changing shape with the sublimation of carbon dioxide.

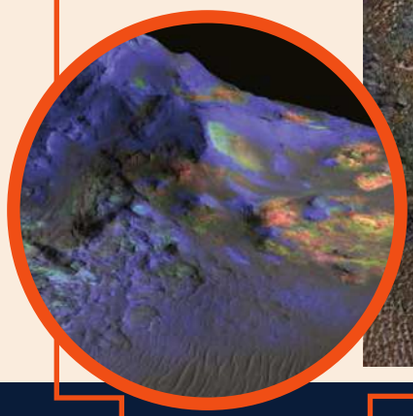


OVER 10 YEARS AROUND MARS

8 June 2015

Glassy debris found

When meteorites hit a planet, the shock waves heat and compress the surface, often fusing sandy grains together to create glass. Impact glass is common on Earth but is hard to detect on Mars as its spectral signature is indistinct. In 2015, researchers find a way to prove that glass is widespread around many meteorite craters, such as Alga, the glass shown here in green. Impact glass can preserve traces of organic chemistry on Earth, so could assist in the search for life on Mars.



2 September 2015

Mars' lost atmosphere

After MRO's confirmation of carbonate minerals on Mars in 2008, the hunt was on to discover larger deposits. The weathering process that creates carbonates also locks away carbon dioxide from the atmosphere, and so weathering could have played a significant role in thinning the Martian atmosphere. In 2015, scientists identify the largest carbonate region so far in Nili Fossae – exposed carbonates are coloured green in this composite of CRISM data and a HiRISE image. The presence of large carbonate deposits supports the idea that ancient surface water was amenable to the development of life.

29 March 2017

50,000 orbits completed

In its 50,000 orbits of Mars the MRO took 90,000 images covering around 99% of the planet (as shown in the picture) and it has observed more than 60% of Mars more than once, gathering over 300TB of scientific data.

2016

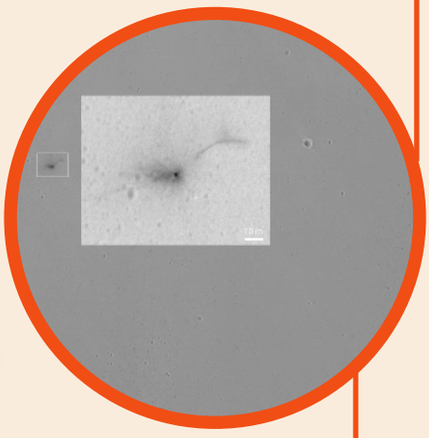
2017

28 September 2015

Water at last!

Following on from the discovery of 'recurring slope lineae' in 2011, evidence for actual water on the surface of Mars remained frustratingly elusive. However many more lineae are subsequently discovered at similar mid-southern latitudes. In 2015 scientists use the CRISM spectrometer to find the next best thing – the distinctive signature of freshly formed hydrated minerals (chemical compounds with water locked into their structure).

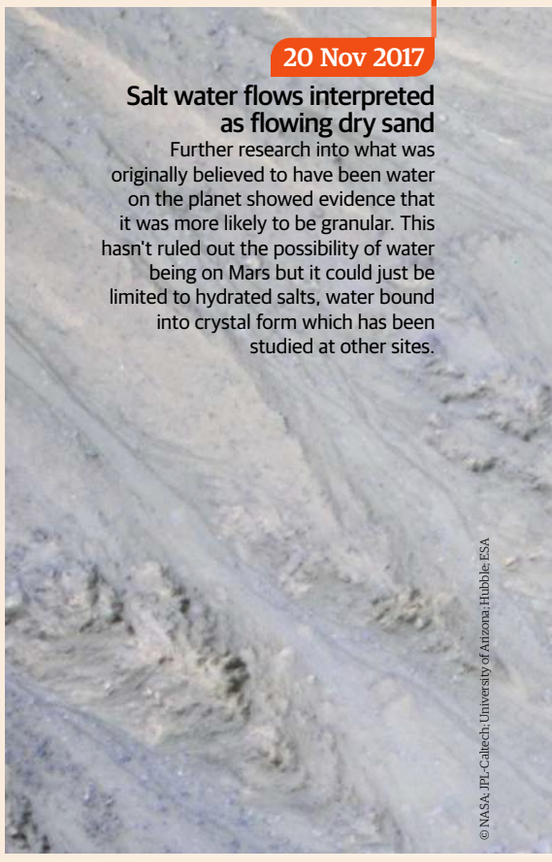
The minerals are found in association with various lineae, including those in Hale Crater (which is pictured here), and the signals are at their strongest where the lineae are widest and darkest. They are thought to be formed by perchlorate salts, which could act as natural antifreeze and keep water flowing at temperatures as low as -70°C (-94°F).



21 Oct 2016

Schiaparelli's crash site found

The Schiaparelli test lander was a joint mission by the Russian space agency and European Space Agency built to test landing technology for Mars whilst also launching the Trace Gas Orbiter in orbit around the planet. On 19 October 2016 the lander crashed on the surface of the planet, leaving three impact sites. The MRO's Context Camera captured its first image of the impact sites: the lander itself, its heat shield and its parachute along with the back shell.



20 Nov 2017

Salt water flows interpreted as flowing dry sand

Further research into what was originally believed to have been water on the planet showed evidence that it was more likely to be granular. This hasn't ruled out the possibility of water being on Mars but it could just be limited to hydrated salts, water bound into crystal form which has been studied at other sites.

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SECRETS OF MARS

HOW A NEW FLEET OF MISSIONS WILL HELP US TO SOLVE THE RED PLANET'S MYSTERIES

Words Nicholas Booth and Elizabeth Howell

THE CHRISTMAS LIGHTS

There are aurorae high above on Mars, just as there are on Earth. In 2014 the MAVEN mission observed what were quickly christened the 'Christmas lights', as they were seen in late December. More recently, daytime aurorae caused by protons from the solar wind have been detected high above the Martian surface.

The Red Planet keeps a tight rein on its secrets. Many enduring mysteries about Mars have taken years of research to resolve, only to be replaced by newer, ever more puzzling ones. If exploring Mars directly over the last five decades has taught us one thing, it is surely that even today – after intense scrutiny from above, on the surface and now probing directly below – the Red Planet can still spring surprises on us.

Mars is a freezing, desiccated desert on which a constant swirl of dust plays havoc with delicate instruments. Worse, mechanical failures and anomalies cause headaches for those who have sent robots in their stead. Even so, most researchers wouldn't have missed any of it for the world.

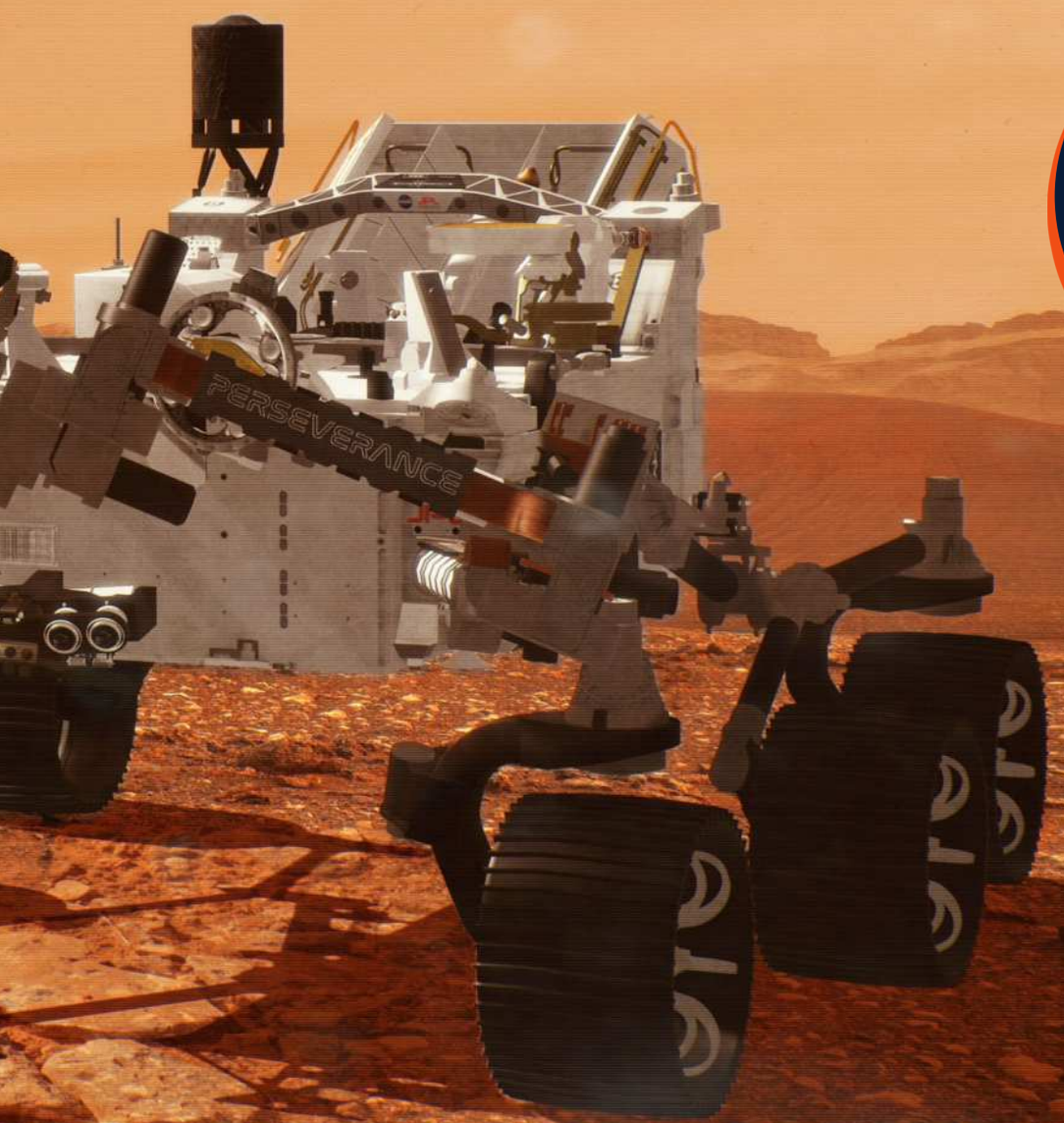
"It's been an amazing journey," says Dr Anna Horleston, a seismologist based at Bristol University. "My study faces south, and as it gets dark I have been able to see Mars rise through the window in the early evening. And then I can look down at my screen at wiggly lines, and know they have come from there."

Those lines represent one of the holy grails of Mars research, the telltale signs of seismic activity. NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) has been making detailed maps of the Martian interior for the first time. It had long been suspected that the Red Planet had a small core and was more Moon-like in terms of its activity, certainly not as seismically active as Earth. Since the InSight landing in November 2018, more than 450 marsquakes have been identified. Residual heat deep within the interior is still causing small-scale seismic waves .

"We have characterised these signals as either high or low frequency," notes Horleston. The higher frequency ones remain extremely puzzling. The lower frequency ones are from

MARSQUAKES

At the time of writing, more than 450 marsquakes have been detected on the Red Planet by the InSight lander. The way in which their signals pass through the interior is revealing the internal structure and layering within the planet itself for the first time.



© Tobias Roetsch, Getty

larger events, some of which have emanated from a rift in the surface called Cerberus Fossae. Observations suggest the faulting seen in Cerberus Fossae is where the release and flexure of energy at depth – and possibly aligned with the faults themselves – is taking place. Some of the team believe that lava as recent as 10 million years old is the cause. The question of how much heat is still radiating outwards from a core that seems to have switched off early in Martian evolution remains one of the greater secrets yet to be revealed.

InSight is all about statistics: the more observations it makes, the greater the accuracy of its findings. For most of 2020, however, its landing site in Elysium Planitia has been windy, drowning out many of the highly sensitive measurements needed to identify marsquakes. Worse has been the cumulative effect of the fine dust which swirls around. "A lot of dust has accumulated on the solar panels," says Horleston. "We knew we would lose power over the course of the mission, but we have more dust than we'd hoped."

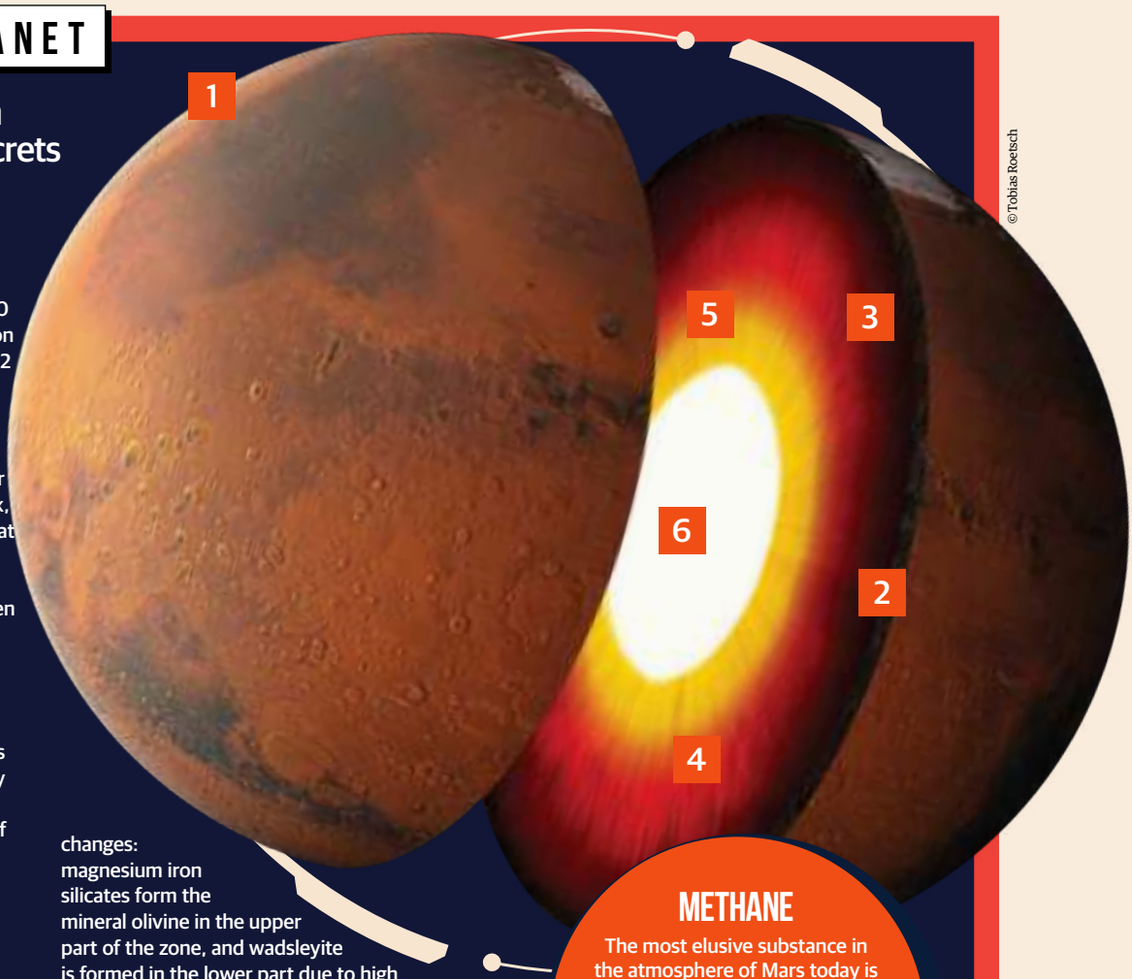
As greater amounts of dust have flowed into the local atmosphere, the amount of sunlight has been reduced. Worse, the spacecraft's solar panels – which provide it with power – have been covered. The mission is now literally running on half the power it had just after landing. Into 2021, that means there will be a delicate balancing act for InSight's operations team. Some instruments may have to be selectively switched off because of power limitations. The lander's robotic arm, for example, should have been put to rest in the spring of 2019. It actually spent most of its first year on Mars being used to scoop, scrape, prod, poke and push. The InSight 'mole' – a heat probe designed to drill into the surface and take measurements – would just not burrow. Even now nobody is sure what the problem was.

The Red Planet often adheres to Murphy's law. The mole would have worked everywhere else on the Red Planet where there have been landings. Now, when it has finally started to do its job, power is becoming an issue. Dust devils have also been seen at other landing sites, which whizz by and act as vacuum cleaners on solar panels. Not so with InSight. It is now essentially hibernating for the winter.

The mission will allow researchers to connect up another important part of the Martian jigsaw puzzle. The atmosphere itself is very dry, cold and tenuous, and is believed to be the remnant of a much denser atmosphere. Understanding how it degraded remains the underlying secret of the Martian climate. The Mars Atmosphere and Volatile Evolution (MAVEN) orbiter has been looking at how the interior of the planet

INSIDE THE RED PLANET

Recent research has been unearthing some juicy secrets beneath Mars' surface



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1 A THICK CRUST

Data from NASA's InSight appears to indicate that Mars' crust is between 20 and 37 kilometres (12 and 23 miles) thick on average. Earth's crust averages between 32 and 48 kilometres (20 and 30 miles).

2 TWO TO THREE LAYERS

The crust is divided into either two or three layers of different types of rock, although there's no confirmation as to what they are yet. Three layers is more likely when analysis of Martian meteorites and geochemical models of the planet are taken into account.

3 MARKING THE BOUNDARY

Using seismology data from InSight taken in 2019, a study by researchers at Rice University concluded the boundary between the crust and mantle is about 35 kilometres (22 miles) below the position of InSight itself.

4 A COOLER MANTLE

InSight found the mantle to be cooler than expected. Largely dormant mantle, it is thought to be richer in iron, potassium and phosphorus when compared to Earth.

5 OLIVINE-WADSLEYITE TRANSITION

The mantle also contains a zone where the mantle's mineral structure changes: magnesium iron silicates form the mineral olivine in the upper part of the zone, and wadsleyite is formed in the lower part due to high pressures and temperature.

6 A HOT CORE

Mars has a metallic molten-liquid core made of iron, nickel and sulphur. It makes up roughly half of the planet's total diameter. Since it doesn't move, Mars doesn't have a magnetic field.

METHANE

The most elusive substance in the atmosphere of Mars today is methane, present in trifling quantities. But the European Trace Gas Orbiter has yet to find any, though recently it may have shown why. A new series of hitherto unsuspected spectral lines may be 'hiding' the underlying signals of methane.

© NASA/JPL Caltech

GOING UNDERGROUND

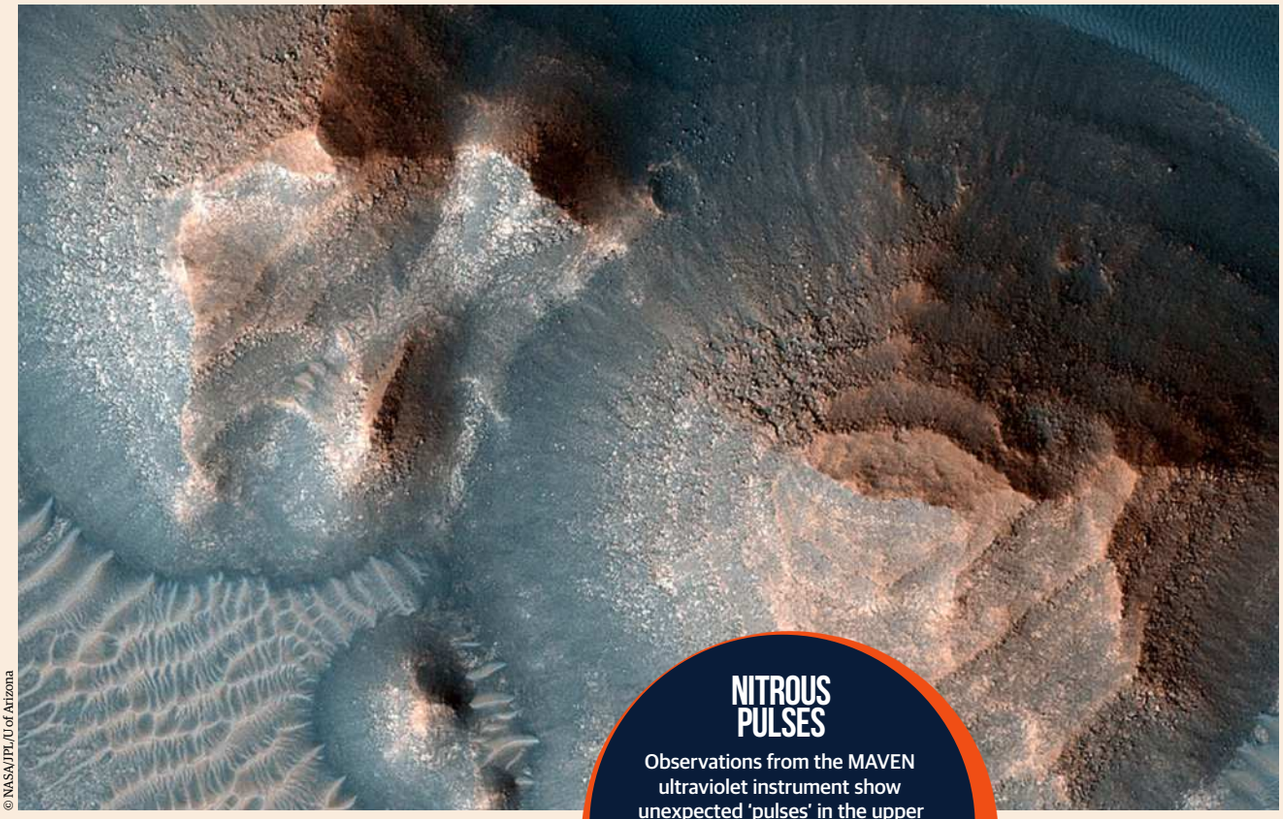
Mars may have had enough internal heat in the ancient past to keep its surface warm. Researchers determined that heat flowing from within the Martian interior would have been sufficient to melt the bottom layers of thick ice sheets in the ancient past. No matter what the surface conditions were like, the heat would have been enough to have sustained life had it formed then.

© NASA/JPL Caltech

Top (clockwise): After much effort and frustration over 2020, the InSight 'mole' – its temperature sensor – has now finally burrowed beneath the surface

The French-British seismometer package shown under its cover, now resting on the surface of Mars

Layered rock on the Martian surface is shaped by wind erosion, as can be seen in this view of Arabia Terra



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NITROUS PULSES

Observations from the MAVEN ultraviolet instrument show unexpected 'pulses' in the upper atmosphere. They are caused by high-altitude winds bringing molecules down into the lower atmosphere, which then 'pulse', accelerating chemical reactions that cause nitric oxide and the ultraviolet glow observed.

relates to how the solar wind interacts with the atmosphere's outmost layers.

"MAVEN was intended to look at the upper atmosphere today as a way of understanding loss to space," says its lead scientist Professor Bruce Jakosky of the University of Colorado, explaining that "The mission's overarching goal was to determine the role that loss of atmosphere to space played in the changing climate through time."

The complex cocktail of chemistry involved shows that the outer atmosphere is selectively pulled apart by the solar wind. "The bottom line is that loss to space accounted for the single largest removal of gas from the atmosphere and was a driving factor in changing the climate some 3.7 billion years ago."

In discovering the first aurora in the upper atmosphere, MAVEN has also shown how solar storms have aided and abetted that loss to space. The enhancement implies that they may have been large enough to have been the determining factor in the overall loss rate in the ancient past. "Solar storms were larger and occurred more often early in history," says Jakosky. "They may have driven the overall loss rate."

Orbital missions have also found that the upper atmosphere is a lot 'friskier' than previously thought. The next arrival, the Hope orbiter, launched in July 2020 by the United Arab Emirates (UAE), will add to that understanding. Hope's instruments will get the 'synoptic view' – a larger overview, fitting in with other missions where there are gaps in our knowledge.

More recently, instruments aboard the Trace Gas Orbiter have watched how the minute amounts of water vapour on present-day Mars have reached higher altitudes in greater amounts during global dust storms. The question of how exactly local dust storms 'go global' remains another mystery.

"It may be that dust storms on Mars are basically chaotic," says Dr Claire Newman, an atmospheric specialist at Aeolis Research in California, who is working across several current Mars missions. "A slight year-to-year difference in the availability of surface dust or local surface wind patterns might make the difference between a global storm or nothing at all."

Due to arrive at Mars on 9 February, the Hope mission will examine the coupling between the lower and upper atmosphere – the exchange of atmospheric energy and mass. "This was highlighted from MAVEN observations as being important," notes Jakosky. "Hope will, by making simultaneous observations of the lower and upper atmosphere and by using synoptic measurements of the lower atmosphere, help

DUST STORMS

In 2018, one of the most fierce global dust storms on Mars covered the planet. Spacecraft watched how the dust fed into the atmosphere, enhancing the amount of atmospheric water vapour taken to the upper atmosphere, which is then broken down and lost to space.

© NASA/JPL-Caltech

"WE WILL CAREFULLY CHECK SUCH DATA TO LOOK FOR OTHER POSSIBLE EVIDENCE OF THE PRESENCE OF BODIES OF WATER"

ELENA PETTINELLI

better understand atmospheric dynamics and the energy transfer."

The forecast for Martian meteorologists is looking good. InSight has the most sophisticated weather-measuring instruments ever sent to Mars. To date, Murphy's law has brought bad luck in obtaining decent wind measurements on earlier missions."Wind is crucial to so many things on Mars," notes Newman. "That includes how the surface erodes and changes over time." Atmospheric scientists also need wind measurements to calibrate their understanding of how localised flows feed into the overall global circulation of the planet. She adds: "Having the highest rate of pressure data" – up to 20 measurements a second on InSight – "has also opened up a whole new world on turbulent variations." The main area of interest is just how different levels in the atmosphere connect with each other. "We've known for a while that we don't quite understand how dust, once it is lifted from the surface, ends up producing high-altitude dust layers, even during the 'clear' season when no major dust storms occur."

WATER IN BLACK BEAUTY

The various elements of the 'Black Beauty' meteorite – discovered in the Sahara Desert in 2011 – show a range of ages of material which fused together on the Martian surface. Most recently, a team in Tokyo has analysed minerals and chemistry in one part of the rock which show there was water present on or in the Martian crust 4.4 billion years ago during an impact which melted part of the crust.

Such measurements will also help in understanding how climate has evolved on Mars. How the Martian atmosphere has changed is inextricably linked with the question of water. The most intriguing insights in recent years have come from itinerant rocks which have been flung from the Martian surface in the ancient past. As remarkable as it sounds, an estimated half a tonne of the Red Planet arrives here on Earth every year. In particular, one truly remarkable meteorite landed in the Sahara Desert in 2011, and is usually known as 'Black Beauty' to those who have had the chance to examine its various fragments.

It is hardly a Rosetta stone, rather an amalgamation of material that has been blasted and fused together on the surface of Mars. Analysis has shown it is made up of a jumble of fragments – 'a hopeless mess' in one assessment – which have fused together at different times throughout the planet's geological history. "The idea is that this meteorite is made up of breccia," says Dr Jane MacArthur of Manchester University, who studied it for her PhD. "That is, it consists of lots of broken fragments in a fine-grained matrix." Meteorite falls have been described as the only free lunch in planetary astronomy. To carry on that analogy, researchers have no idea who the chef was, what ingredients were used or even which shift they were working on. Regarding Black Beauty, what we're trying to do is unravel all the component parts in MacArthur's assessment.

© ESA

Left: Wind has shaped the visible surface of the south polar ice cap, and beneath the surface it has been suggested there may be 'lakes' of liquid water

Bottom left: Over the next decade, samples will be taken by the Perseverance rover in Jezero crater and left as caches to be picked up by a later 'fetch' rover for return to Earth

It is unusual in that it is clearly composed of rocks which have been excavated near the surface and not from deep within the interior. As such, Black Beauty shows how the crust and the atmosphere have interacted over time. In places, its youngest material – roughly 1.5 billion years old – contains ten-times more water than other Martian meteorites. Taken at face value, this suggests much more water has flowed on the Red Planet in the recent past than was previously believed. But is there liquid water on Mars today?

If there is, it will have long since frozen beneath the planet's surface in an extensive aquifer. So far the inference of subsurface ice has been made from radar measurements taken from orbit. Radar signals penetrate the surface, and their reflection indicates the presence of ice in several places.

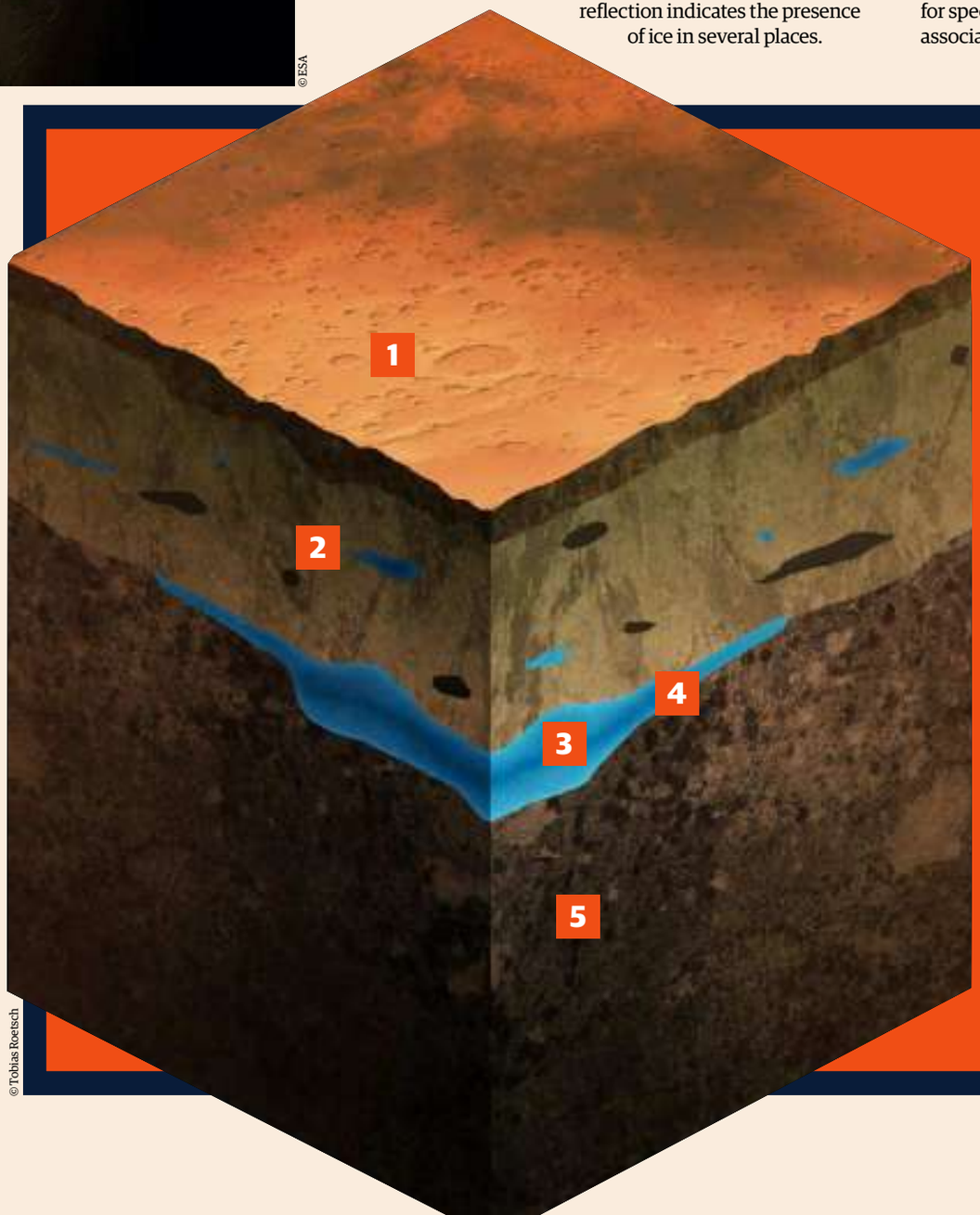
WATER AT THE POLES

Mars today is freezing, with no signs of liquid water on the surface. But repeated passes over the south pole of the planet by the Mars Express radar instrument have shown that there may be 'lakes' underneath them, increasing the likelihood of life being present.

In particular, during the summer of 2018, a discovery was made of what was described as a large lake under the south pole. What lead scientist Dr Elena Pettinelli of Roma Tre University called "anomalously bright subsurface reflections" were observed by a radar instrument on the Mars Express orbiter.

Now, several years later, greater numbers of passes by the same instrument have refined the observations. A total of 134 'profiles', as the team calls the radar observations "are crossing each other and covering a larger area". Centred on what they interpreted as a lake, a different analytical technique has now been employed. This, the team points out, is the exact same procedure used to look for subsurface water under terrestrial ice sheets in polar regions.

"We have analysed the radar signals looking for specific features that on terrestrial radar are associated with the presence of liquid water at



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WATER ON MARS

1 DRY SOIL
Martian soil forms a dusty layer. It's made up of nutrients such as sodium, potassium, chloride and magnesium.

2 SIGNS OF ICE
Ice which once formed on the surface of Mars is thought to have become buried, leaving an immediate permafrost subsurface with young ice in its pores.

3 POCKETS OF WATER
Water ice is locked within cavities across the mid-latitudes of the planet. Some chunks of frozen water have been found just beneath the surface.

4 SUBSURFACE RESERVOIRS
Underground lakes are thought to exist far beneath the surface. A high level of salt or heat from Mars' interior could even result in them being liquid.

5 THE FOUNDATION
The water would lie above an impermeable bedrock, which has a high concentration of sulphur.

the base of the ice sheets," says Pettinelli. This new approach implies that subglacial meltwater was formed elsewhere on Mars in the ancient past, when the climate was more clement.

The findings are controversial. Some believe the observations are more to do with how the radar is modelled. Others think the water would be more sludgy and is perhaps a subsurface layer of high groundwater abundance. Water would have to be very salty and heated to stay warm.

The Italian team acknowledges there is no current explanation for any subsurface heat sources on Mars, unlike Antarctica, which hosts several subsurface lakes which are kept above freezing. Hypersaline water could also remain above freezing. "We think that perchlorate salts, that are ubiquitous on Mars, could help to keep the water liquid," Pettinelli says. "We will carefully check such data to look for other possible evidence of the presence of bodies of water."

All these questions are the curtain raiser for the next decade, when space agencies will attempt to return samples from Mars. The Red Planet is evidently a complex world – no less complex than our own, even though it doesn't have plate tectonics or an ocean. "Mars is also an excellent place to study planetary processes that tell us about habitability and the potential for life, the evolution of climate and the atmosphere and the evolution of a terrestrial planet during its first billion years," concludes Jakosky. "It's a compelling planet, with lots left to explore to find answers to major questions."

NICHOLAS BOOTH
Space science writer
Nicholas worked on *Astronomy Now* and served as a science writer for national newspapers. He co-wrote *The Search for Life on Mars*.

ELIZABETH HOWELL
Space science writer
Elizabeth holds a PhD in aerospace sciences and is a contributing writer to **Space.com**. She co-wrote *The Search for Life on Mars* with Nicholas Booth.

Below:
Dust storms on Mars can whip up and cover the whole of the surface. This was the view in 1971 when Mariner 9 – the first successful orbiter – arrived. As the dust cleared, the giant volcanoes were seen for the first time

© DanielleDondersMothershipPhotography

2021 ONWARDS: PLANS FOR STUDYING THE RED PLANET

On 9 February 2021, the UAE's Hope mission – a small test orbiter – arrived at the Red Planet, carrying mainly American instruments. Next the Chinese Tianwen-1 mission entered a long, looping orbit. A few months later a lander was dropped from the orbiter, which will see the starting gun on China's own ultimate ambitions to return samples – as it has just done from the Moon.

NASA's Perseverance landed on Mars on 18 February 2021. Along with other scientific objectives, it will be looking for signs of past life on the Martian surface. It barrelled straight in, aiming at a bullseye 45 kilometres (28 miles) across: Jezero crater. Sadly two European landers have crashed in this same region already – Beagle 2 and Schiaparelli, victims of the so-called 'Mars curse' in which spacecraft unpredictably crash-land on the surface of the Red Planet. As the sky crane dropped the rover down there was the usual comms blackout 'seven minutes of terror' as NASA waited for the signals to confirm Perseverance's successful touchdown.

2021

ROSALIND FRANKLIN

This European rover – built in Stevenage – will be taken down to the surface by the Russian Kazachok lander. Because of problems with its parachute systems and complications from the coronavirus pandemic, its launch has been pushed back to the autumn of 2022. Both lander and rover will land in Oxia Planum in the spring of 2023.

© ESA

2022

2023

TERA-HERTZ EXPLORER (TEREX)

The Mars Terahertz Microsatellite is a Japanese mission designed to take both an orbiter and lander to Mars. The latter will measure oxygen isotope ratios in the atmosphere to better understand the chemical reactions that replenish the Martian atmosphere with carbon dioxide.

© TEREX

2024

2025

MANGALYAAN-2 (MARS ORBITER MISSION 2)

India's follow-up mission to its first orbiter may carry a lander and rover as possible additions. While there is no official announcement of when it will be launched, it will likely be in 2024 at the earliest.

Source: Wikipedia Commons © Nesnad

2026

2027

MARTIAN MOONS EXPLORATION (MMX)

Japan plans to send a probe to Mars' largest moon Phobos in 2024. It will drop a small lander on Phobos, collect samples and return them back to Earth. The samples are expected to arrive in July 2029.

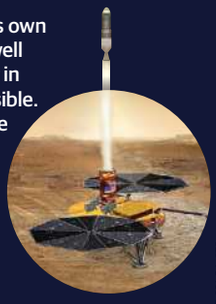
© NASA

2028

2029

MARS SAMPLE RETURN

After launch in July 2026, a lander will carry its own Mars ascent rocket for the return journey, as well as a 'fetch' rover. This will land in Jezero crater in August 2028, as close to Perseverance as possible. The rover is a 'minicab' designed to retrieve the samples and take them to the ascent rocket, which will fire into low-Mars orbit with the sample-return canister in spring 2029. A European-built orbiter will 'catch' the canister with the samples inside it and then transfer them to a return mission, which will land back on Earth some time in 2031.



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2030

2031

NASA'S PERSEVERANCE ROVER TAKES ITS OWN WHEEL FOR MARS DRIVES

AUTO-NAVIGATION ON THE RED PLANET: "IT'S A ROVER DRIVER'S PARADISE"

Words Meghan Bartels

NASA's Perseverance rover is picking up the pace on Mars thanks to technology that helps the robot avoid running into trouble on its otherworldly drives. That technology, called AutoNav, is a navigation system that maps terrain and plans routes without the rover needing to rely as heavily on guidance from Earth. AutoNav is four or five times more powerful than equivalent technology tested on NASA's previous Mars rover, Curiosity, which means Perseverance will be able to take more direct routes and travel faster, in turn allowing the rover to do more science in the same amount of time.

"We're going to be able to get to places the scientists want to go much more quickly," Jennifer Trosper, project manager for the rover at NASA's Jet Propulsion Laboratory (JPL) in California, said. "Now we are able to drive through these more complex terrains instead of going around them. It's not something we've been able to do before."

The AutoNav process doesn't cut out human drivers entirely – it just increases the rover's autonomy where possible. "We have a capability called 'thinking while driving'," said Vandi Verma, a senior engineer, rover planner and driver at JPL. "The rover is thinking about the autonomous drive while its wheels are turning."

Other features on the rover also help increase speed. Its wheels have a larger diameter, narrower width and wavier tread pattern, which mission engineers designed to increase traction and durability on Mars. Perseverance also carries an entirely separate computer devoted to navigation, and the new rover's belly clearance is higher, making a wider variety of terrain safe for exploring.

Perseverance is faster and easier to control than past rovers

© NASA / JPL-Caltech

All told, the improvements implemented for Perseverance mean the rover could travel as fast as 120 metres (393 feet) per hour – just over the length of a football field – compared to Curiosity's much slower speed of 20 metres (66 feet) per hour. That would put Perseverance's top speed at about 0.12 kilometres (0.07 miles) per hour. Increasing rover speed for Perseverance is important because mission scientists hope to direct the rover to cover a total of 15 kilometres (nine miles) over the course of its mission.

That's exciting not just for scientists, but also for the humans helping Perseverance navigate, who get to enjoy more of the Red Planet's scenery in Jezero crater. "Jezero is incredible," Verma said. "It's a rover driver's paradise. When you put on the 3D glasses, you see so much more undulation in the terrain. Some days I just stare at the images."

SURVIVING ON MARS

BARREN, COLD AND UNINHABITABLE – WILL MANKIND BE ABLE TO MAKE A HOME OUT OF THE RED PLANET?

Words Gemma Lavender

Stranded on Mars. That's the fate that befalls one unfortunate astronaut in Ridley Scott's film *The Martian*, based on the novel by Andy Weir. With no way to contact home, he must rely on his skills and the equipment available to stay alive in the face of deadly Martian elements.

While the film and book are both works of fiction, it is true that going to Mars will be the most dangerous crewed space mission ever attempted. There are dust storms, radiation, an unbreathable atmosphere, fierce coldness and low gravity to contend with, while the astronauts themselves will have to constantly be in top physical and mental condition in the most challenging of environments. Should anything go wrong, it is an 18-month wait for a new launch back home, and then a further eight months travel time. The first astronauts to step foot on Mars will have to look after themselves.

The motto for a future Mars mission might read 'be prepared'. Knowing that astronauts will be on Mars by themselves for a long time, any mission will require all the equipment they could conceivably need to survive, plus back-ups and spares for when things inevitably break. Carrying all this cargo at once would need a big

OUR PATH TO MARS

Steadily, and with the right technology, we're hoping to land man on the Red Planet

RELYING ON EARTH

Mission length: 6-12 months
Time to return to Earth: hours

Humans in orbit
Rockets have allowed astronauts to gain access to space via low-Earth orbit.

International Space Station
We've managed to master the very basics of getting to Mars on the International Space Station.

ship, requiring a large amount of fuel. Instead, the idea is to send as much as possible to Mars ahead of the astronauts in the form of pre-cursor missions, so that supplies and a power source is waiting for them when they arrive. One of these pre-cursor flights will also act as the astronauts' return vehicle. It will make its own rocket fuel by reacting a small amount of hydrogen that it carries with the plentiful carbon dioxide in the Red Planet's atmosphere. This chemical reaction produces oxygen that can be used as rocket propellant. So, if anything does go wrong when the astronauts first touch down on Mars, there will be a ship there ready and waiting, guaranteed to be able to bring them home. Their landing craft will also double up as a habitation module, or at least part of one – a place for them to live and work. When the crew is ready to return to Earth, the habitation module is left behind for the next mission to use. An additional habitation module is left behind with each mission, gradually forming the beginnings of a permanent base on Mars.

An advocate of this mission plan is Kevin Nolan, author of the book, *Mars: A Cosmic Stepping Stone*. He highlights that giving astronauts a decent chance of succeeding and surviving in their mission is going to take patience – rushing to Mars would make the astronauts unlikely to come home again.

"If we're to set people on the surface of Mars then it most likely cannot happen before 2040," Nolan says. "The notion of placing people on the surface for a required 500-day stay there requires significant resources such as supply missions two years in advance, landing miniature nuclear power stations on the surface, and providing a facility to manufacture the fuel to be able to return home. All of these are decades away – so this time period is the most likely for actual human missions to the surface."

The dangers of living on Mars are environmental. The atmosphere is 95 per cent carbon dioxide with the remaining five percent being made up of nitrogen and argon, and a measly 0.1 per cent of the atmosphere being oxygen. Contrast that with Earth's friendly atmosphere, which contains a breathable 21 per cent oxygen and 78 per cent nitrogen. To us, the Martian atmosphere is deadly.

The temperature on Mars varies wildly. In the summer, near the equator, temperatures can actually reach above the freezing point of water, but the air pressure is so low (just 0.6 per cent of Earth's surface pressure) that water still cannot exist as a liquid, and it wouldn't feel very warm. In winter, at the poles, the temperature can plummet as low as -125 degrees Celsius (-193 degrees Fahrenheit).

"UNDER SUCH LOW PRESSURE YOUR BLOOD WOULD BOIL, SO A SPACESUIT IS ESSENTIAL TO SURVIVING ON MARS"

The Red Planet is an extremely barren place

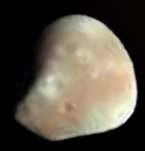
LANDING ON A FOREIGN BODY

Mission length: 1-12 months
Time to return to Earth: days

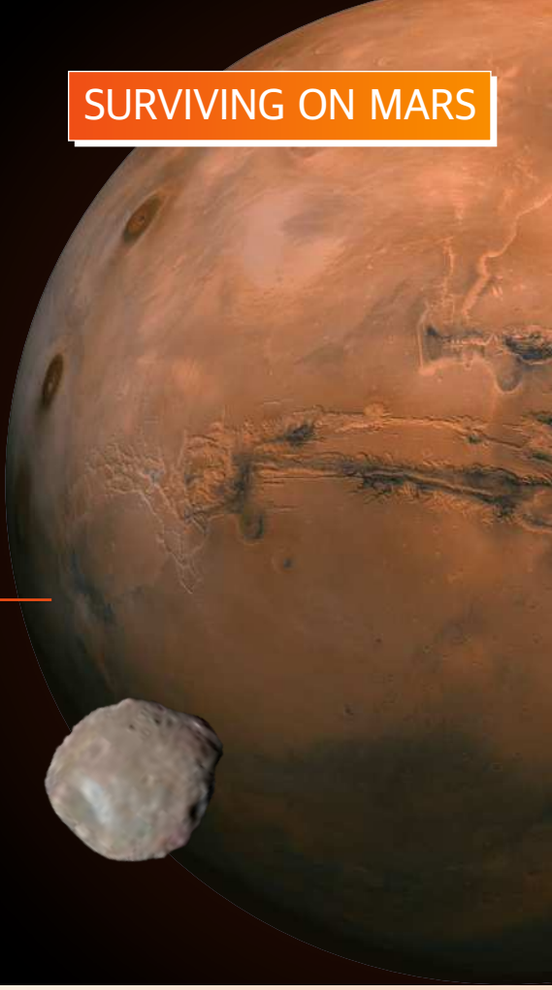
GETTING READY FOR MARS

Mission length: 2-3 years
Time to return to Earth: months

Humans on asteroids
By visiting an asteroid redirected to lunar orbit, we're hoping to expand our manned space exploration capabilities.



Manned exploration of the Red Planet
We're aiming to gain planetary independence by landing on Mars, its moons and other deep space destinations.



So Mars' atmosphere is not a mixture that you can breathe, and the temperatures mean that you would freeze. Not only that, under such low pressure your blood would boil, meaning a spacesuit is essential to survive on Mars. Specially designed suits are in development that will transform any budding space adventurer into Buzz Lightyear.

NASA's new Z-series of spacesuits are prototypes of what men and women may one day wear when they are trudging around the surface of the Red Planet. The key difference between the Z-series and other spacesuits is that they will be designed to make walking easier, which astronauts haven't really needed to do when floating in space. Even when the Apollo astronauts ventured to the Moon, they only had to put up with an ungainly gait for short excursions onto the surface. When spending 500 days on Mars, the astronauts are going to want to wear something that is practical and flexible, and not as stressful on the human body. The Z-series achieves this by having bearings in the shoulders, waist, upper legs and ankles that allow greater freedom of leg movement and firmer footing. The upper torso of the latest version of the suit - the Z2 – is a hard shell, so if an astronaut tumbles, they are less likely to damage or rip the suit. In Mars' cold, low pressure, unbreathable air, that would be deadly.

The Z-series spacesuits will essentially be life-support systems for the Mars dwellers. Not only do they offer protection against the cold and the poisonous atmosphere, they also provide air, water and even food, and monitor the astronaut's health. Scientists at NASA's Johnson Space Center are currently working on an advanced Portable Life Support System

NEXT GENERATION SPACESUIT

The Z2 spacesuit is specifically designed for roving the Red Planet

Moving with ease
Unlike most spacesuits, the Z-series sports a waist bearing, which allows extra mobility when walking as the astronaut swings their hips.

Hard shell
The torso on the Z2 is built out of an impact-resistant hard composite, increasing its durability to protect the astronaut inside.

Docking port
The Z-series of spacesuits are unique in that they feature a docking port on the back that allows the suit to connect with airlocks on vehicles and habitats.

Life support
The advanced Portable Life Support System contains batteries, a carbon dioxide remover, humidity monitors, oxygen and suit pressure controls.

Sure footed
An ankle bearing in the suit's boots allows the user to step sure-footed over rough terrain.

SPACESUIT DESIGNER

AMY ROSS, NASA

"The Z-series spacesuit is designed with very good walking capabilities. I participated in the spacesuit field-testing, where we wanted to understand what a suit that we built for the Moon or Mars would be like doing its job, and the only way to do that is to go out and see. How does the subject in the suit do geology for instance? We monitor how well the suit allows them or doesn't allow them to do that job, and what features we need to focus on for further development. The strategy we're taking right now is looking at what the most challenging aspect is. For mobility on Mars, it is being able to walk on the surface. We try to design so that we're capable of that, so when we have to build a suit for one specific mission, we already have the information and capability to build a spacesuit that's going to work."

(PLSS) that will attach to the Z-series suit. The PLSS will control the suit's pressurisation, as well as remove poisonous carbon dioxide that has been exhaled by the astronaut, which would otherwise build up dangerously in the suit's air recycling system.

The importance of a safe spacesuit becomes clear once you look at what would happen should you become exposed to the Martian air. Imagine you are on that first human mission to Mars. You open the airlock, climb down the ladder and put that first booted footprint into the Martian dust. You step out and go for a short walk around the landing site. Unfortunately you have landed close to a gorge. Unaccustomed to the low gravity, you fall in, smashing your helmet's visor on a rock (in reality, a spacesuit's visor is extremely tough and would be hard to break). The oxygen in your helmet quickly leaks out and within 15 seconds you lose consciousness from the lack of oxygen. The low pressure causes your blood to boil, making your skin and organs expand. Your body becomes swollen, but your blood does not evaporate – instead as it boils it sheds heat quickly and, in the cold temperatures of Mars, actually freezes. The low pressure and lack of oxygen will kill you in less than a minute.

Another scenario is that one of your suit's air valves might develop a small but deadly leak. You probably won't hear the air whistling out through the hole, as the thin atmosphere muffles sound, but the PLSS on your back will alert you to the fact that your oxygen and pressure is decreasing, while carbon dioxide leaking in from outside is building up, slowly suffocating you. Fortunately, air valves, tubes and other life support fittings will be standardised not only on the suit, but where possible in the habitat and any vehicles, making repairs relatively simple.

A nifty feature of the Z-series suit is that the astronaut enters the suit through a port at the back – that same port can be used to 'dock' with vehicles or even habitat buildings and allow safe passage inside from the suit. In many ways, a Mars habitat will be an extension of the life support system of the spacesuit. It will need to keep the astronauts safe and comfortable for 500 or more days without being resupplied, and with only limited repairs possible should damage be incurred. The habitat could be hit by dust storms or even a meteorite fall – as the atmosphere is so thin on Mars, more meteors are able to reach the surface intact than on Earth.

As discussed earlier, the habitat is likely to be made from crew modules that landed on the surface during the pre-cursor flights. However, an alternative method would be to print and assemble a habitat on Mars using a 3D printer. NASA has commissioned dozens of plans and designs of habitats in the past for use on both Mars and the Moon. For example, scientists in the Aerospace Engineering Sciences Department at the University of Colorado produced a report on the engineering design of a proposed Mars habitat, highlighting that each life support system needs several layers of redundancy. For example, if the water recycling system or the

LIVING ON ANOTHER WORLD

Turning the Red Planet into our home will involve many adaptations and alterations

Greenhouses
Astronauts will be able to grow their own crops in greenhouses, meaning that they could keep feeding themselves indefinitely.

A place to live
Hermetically-sealed habitats that are entered through airlocks will support the astronauts. However, conditions are likely to be cramped, with little privacy.

MARS EXPERT

BOB ZUBRIN, MARS SOCIETY

"The basic idea is to explore Mars with a 'travel-light' philosophy, so rather than building giant spaceships in orbit loaded with all of the food, water, air, fuel and oxygen required for a round-trip mission, we try to make the most important of these on Mars. First you'd send a Mars return vehicle with no one in it. That lands on Mars and reacts a small amount of hydrogen that it brought from Earth with carbon dioxide in the Martian atmosphere to produce a large supply of methane, oxygen rocket propellant and oxidiser. So now you have a fully fuelled Earth-return vehicle sitting on the Martian surface. Then you shoot the crew out to Mars in a habitation module that they use as their house while they are on Mars exploring. Then after 18 months of exploration they get in the Earth-return vehicle and fly back, leaving the habitation module on Mars. Each time you do this you add another habitat to the base and before you know it, you have the first human settlement on another world."

Hidden danger
The pink sky on Mars looks calm and serene, but with the onset of Martian summer, huge dust storms can blow up that turn the sky dark and cover solar panels.

Phoning home
Talking with mission control or loved ones back home will be difficult for Mars astronauts. Because our two planets are so far away from each other, a signal will take up to 20 minutes to reach from one planet to the other.

Return vehicle
The way home will already be set up on Mars when the astronauts arrive. Early pre-cursor missions will deploy habitats, equipment and a spacecraft to fly the crew home prior to the astronauts' arrival.

Low gravity
The gravity on Mars is just 38 per cent of the gravity on Earth. Astronauts will have to get used to living and working in this low gravity for months on end.

Spacesuit
The astronauts' space suits are mobile life support systems that keep the wearers alive despite the cold and low pressure on the surface of Mars.

MARS MISSION EXPERT

STEVE SQUYRES, NASA

"Despite having devoted my career to exploring the Solar System with robots, I am a strong advocate of human exploration, particularly on Mars. Humans have an extraordinary ability to function in complex environments, to improvise, and to respond quickly to new discoveries. Robots, in contrast, do best when the environment is simple and well understood, and when the scientific tasks are well defined in advance. The capabilities of humans surpass those of robots in complex environments. And there is no planetary environment where humans can operate in the foreseeable future that is more complex than the Martian surface."

The Mars Curiosity rover (pictured) along with other spacecraft have allowed us to observe the Red Planet before stepping foot on its soil

power generator breaks down, a back-up would be available to step in, and there would be a back-up for the back-up too, just in case.

A Mars habitat also needs to be capable of providing food. Surprisingly, scientists believe that Martian dirt would be suitable for growing crops in. Dutch scientists have tried this in their laboratory, by making their own 'Martian dirt', based on what the Mars rovers and the older Viking missions of the 1970s have taught us about its composition. The 14 species of plant grown in the Martian dirt replica flourished; they germinated, flowered and survived the 50 days that the experiment lasted. Dirt on Mars lacks nitrogen and liquid water, which plants need, but contains many other nutrients that plants can feed from. The introduction of bacteria into the dirt can provide a source of nitrogen, and the humble watering can will supply the water. Future Mars habitats will therefore have a greenhouse section where crops are grown. These will have to be artificially lit, as the daytime Sun on Mars is fainter than it is on Earth. Nevertheless, starvation should not be a problem for the Mars population.

Obtaining water should be a simple task too. Mars is a dry world, but there is plenty of water on it, in the form of ice. There are the ice caps at the poles, but there is also subsurface permafrost ice just below the surface, stretching down to the planet's mid-latitudes. So water could be obtained by melting this ice. Another option is to copy the stranded astronaut in *The Martian*, who burns hydrazine rocket fuel to release hydrogen, and combines this hydrogen with oxygen produced by his habitat's 'oxygenator', which splits oxygen from Mars' carbon dioxide atmosphere.

A habitat will also act as a shelter against the elements outside. Mars has no global magnetic field and a thin atmosphere, so it cannot deflect solar radiation. The habitat will contain a shielded room to protect from the radiation emitted by solar flares. Unfortunately, the astronauts will need to rely on fate or good luck to protect them from cosmic rays while out and about on Mars – prolonged exposure out in the open will increase the chances of the astronauts getting cancer from space radiation. But the biggest natural hazard on Mars is the wave of dust storms that blow up every Martian summer. The biggest ones can envelop the entire planet, coating solar panels with dust and concealing the Sun in the sky. Martian dust is made of very small particles, and the wind speeds are not very high in the thin atmosphere. So a habitat is not going to be blown over in a storm, but it is possible that the dust could find its way into the living area or into electronics, causing serious damage. However, the Mars rovers have survived many dust storms; up until Opportunity could take no more from the Martian elements the biggest problem they faced was a loss of power as their solar panels became covered in dust. Fortunately, astronauts can just wipe the panels clean.

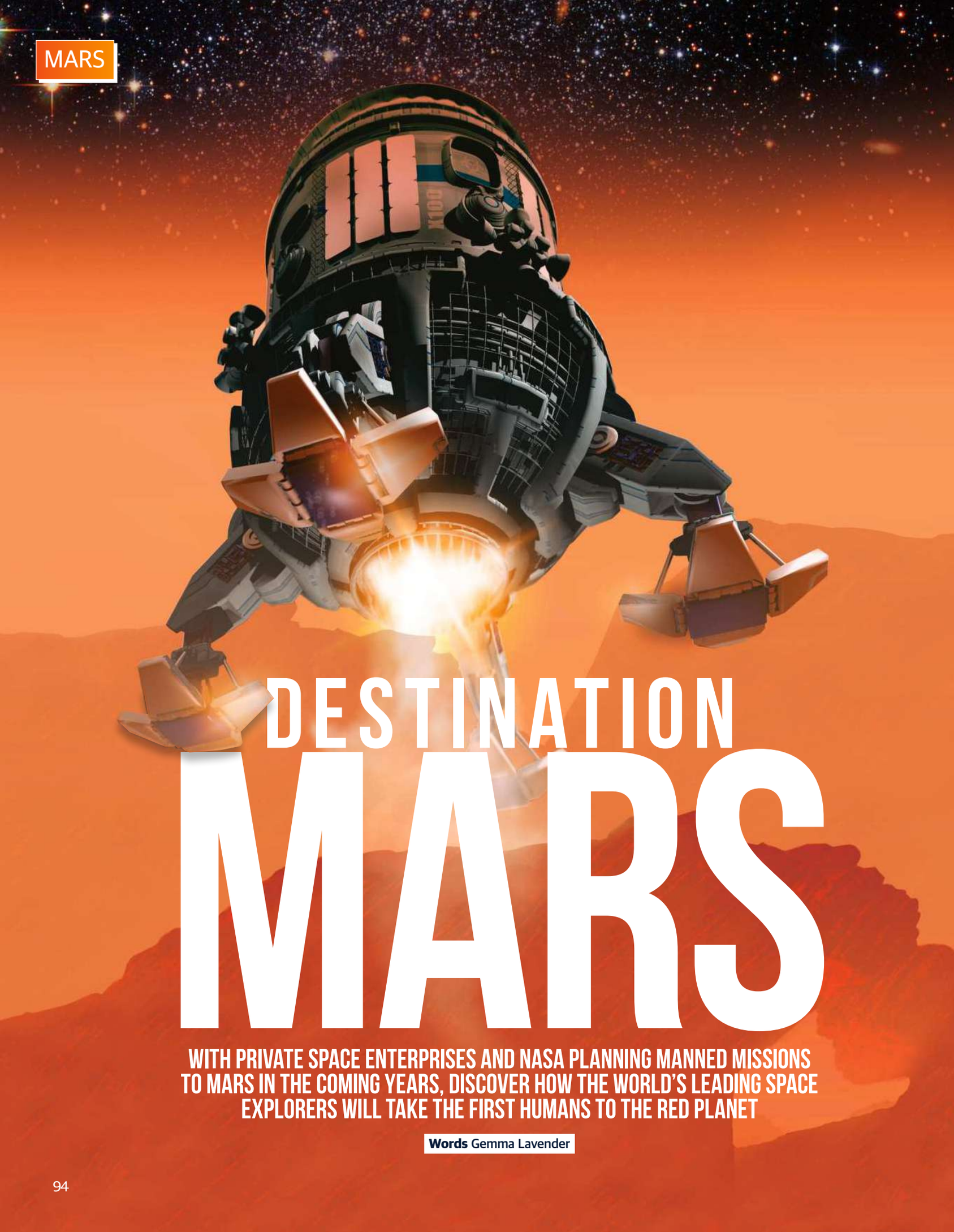
The biggest obstacle to surviving on Mars may not be the lack of air, or the cold, radiation or planet-sized storms. The biggest killer could be loneliness. Even if you not stranded alone like the hero in The Martian, and you are with six to ten other astronauts, you are still 200 million kilometres (124 million miles) from your friends, family and everything you knew on Earth. Your calls to home will take 20 minutes to get there, and then another 20 minutes to be returned. Scientists are attempting to study how long-term exposure and isolation in space affects mental health – the year-long mission of NASA astronaut Scott Kelly on board the International Space Station was part of this research. Spending over two years in a challenging and alien environment will tax even the most mentally strong – unlike a mission to the Moon, you can't be back home in three days.

The initial wave of astronauts who will travel to explore Mars are going to need to be tough, both mentally and physically, and they and their ground teams will need to be extremely well prepared for the challenges that meet them during their extensive mission. However, with scientists and engineers back on Earth supporting the team, years of intensive training to help them, and a knack for ingenuity and adaptation, perhaps it will be possible to survive on Mars after all.

The team behind NASA's Mars Science Laboratory

© Getty Images; NASA; JPL

A researcher performing simulated 'Martian' surface activities at the Mars Society Desert Research Station in Hanksville, Utah



DESTINATION MARS

WITH PRIVATE SPACE ENTERPRISES AND NASA PLANNING MANNED MISSIONS TO MARS IN THE COMING YEARS, DISCOVER HOW THE WORLD'S LEADING SPACE EXPLORERS WILL TAKE THE FIRST HUMANS TO THE RED PLANET

Words Gemma Lavender

It was former Apollo astronaut and second man on the Moon Buzz Aldrin who uttered the words, "Forget the Moon, let's head to Mars!" This is something that mankind has been working to achieve since the Sixties. Fleets of flyby missions, orbiters, rovers and landers have been sent on one-way missions to shape our understanding of the Red Planet, setting down the groundwork that will one day lead to the moment an astronaut sets foot on Martian soil for the first time.

At an average distance of around 225 million kilometres (140 million miles), Mars might not be as close to the Earth as the Moon or Venus, but the ruddy-coloured planet's potential to provide us with information to sate our appetites for knowledge as well as the opportunity to expand our species to another world, today encourages generations of scientists to overcome this distance with relative ease. However, it was not always this way.

The Soviet Union was the first country to launch robotic missions to Mars, with a number of failed launches and probes in the Sixties. By the Seventies, however, they had competition from the Americans. With two countries setting their sights on the Red Planet, the race was well and truly on, but who would get there first?

On 19 May 1971, the USSR's Mars 2 successfully raced through the last of Earth's atmosphere with the Red Planet in its sights. Russia was in with a good chance of winning this round of the Space Race. With the successful launch of Mars 3 taking place a mere nine days later, this only reaffirmed the Soviets' confidence.

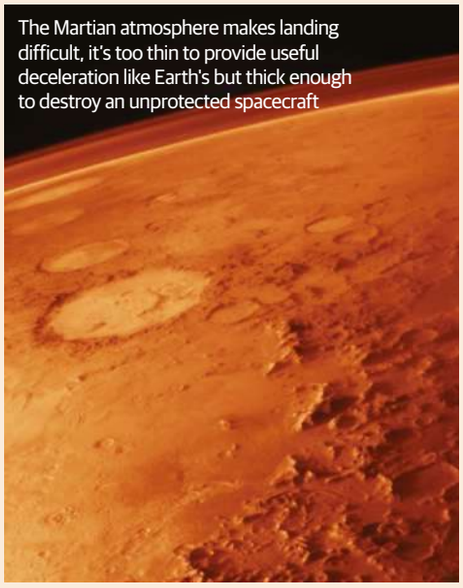
However, on 30 May 1971 NASA released Mariner 9 into the skies above Cape Canaveral, hot on the heels of Mars 2 and Mars 3. It reached Mars by 14 November of the same year, beating the sluggish Mars 2 and 3 by a few weeks. Even so, Mariner 9 had to wait out months of relentless dust storms raging across Mars before it could take any of the 7,329 clear images of the Red Planet that it ultimately beamed back to anxiously waiting scientists on Earth. It saw river beds, craters, canyons, great extinct volcanoes such as Olympus Mons, as well as obvious signs of erosion from water and wind.

Following Mariner 9's successful visit, in 1975 NASA launched the twin Viking missions, each one combining an orbiter and lander. But that was it until the mid-Nineties. Since then several robots have been sent to Mars, determined to be the first to underpin the principles which will one day allow humans to set foot on the planet's surface. Satellites have included NASA's Mars Global Surveyor and Mars Reconnaissance Orbiter, and the ESA's Mars Express, as well as the successful Phoenix and Pathfinder landers, while the Spirit, Opportunity and Curiosity rovers touched down on Mars to inspect the Martian soil for signs of life and to take a few snaps of their new home.

However, as we push for greater feats the rovers don't seem to be enough. We need something more sophisticated, according to advocate of the manned exploration of Mars and American aerospace engineer, Dr Robert Zubrin of the Mars Society. We need to go to Mars ourselves.

"I do favour sending robots to Mars and I am very happy that we're doing that," says Zubrin. "They are just the advance scouts and you know, the rovers, I love them, but there's nothing they can do that we [humans] couldn't do a thousand times faster." While the work of the rovers has provided us with an incredible amount of information, signatures of past life on the Red Planet, such as fossils could easily be overlooked by the robots. "You could parachute 100 rovers [to Mars] and you would never find a fossil," Zubrin explains. "Finding fossils involves hiking through lots of terrain, it involves pick and pickaxing work and it involves diligent work such as carefully splitting open shells to find preserved fossils. This is way beyond the ability of robotic rovers and if you're talking about whether humans could settle on Mars, then clearly, you have to send humans."

So to Mars humans must go. And in a change of dynamic, agencies and organisations, including private companies, are now looking past unmanned missions and instead are focusing on landing the first man on the Red Planet in a step that makes science fiction a reality. The feat has become a race once again. And Zubrin thinks he knows how to win the race to the Red Planet. In the Nineties he developed a daring plan that he called Mars Direct. "The basic idea of the Mars Direct mission is to explore Mars with a travel-light philosophy," he says. "Rather than building giant spaceships loaded with all of the food, water, air, fuel and oxygen required for a round-trip mission, we try to make the most important of these on Mars."



The Martian atmosphere makes landing difficult, it's too thin to provide useful deceleration like Earth's but thick enough to destroy an unprotected spacecraft

The Orion module replaces the now cancelled Constellation Program as our future hopes to send man to Mars

For example, Zubrin proposes that an unmanned mission go ahead first, carrying with it an Earth-return craft and the ability to make rocket fuel on Mars by reacting hydrogen with the carbon dioxide in Mars' atmosphere to create the methane and oxygen rocket propellant and oxidiser. "So now you have a fully fuelled Earth-return vehicle waiting on the Martian surface," he says. "Then you shoot the crew out to Mars and because the return vehicle is waiting on Mars, they don't need to fly to Mars on a giant spaceship, they just fly to the Red Planet in a habitation module that lands in the vicinity of the Earth-return vehicle."

After 18 months on the surface, the astronauts then head home in the Earth-return vehicle, leaving the habitation module on the Red Planet. But then a second manned mission is launched, delivering another habitation module to the surface, and then a third and a fourth. "Before long you have the first human settlement on another world," says Zubrin. "There is nothing in this that is beyond our technology; we can do this."

Other organisations are clamouring to be the first to touch down on the Red Planet. Most notably, SpaceX's Elon Musk has already stated that he intends to go to Mars, while former private astronaut Dennis Tito launched Inspiration Mars, an organisation that planned to send two humans on a flyby mission of Mars in 2018, which got pushed back to 2021 before being made entirely defunct. It was a plan that Zubrin himself pitched to NASA in 1995, but they didn't take him up on the idea.

"I DO FAVOUR SENDING ROBOTS TO MARS... BUT THEY ARE JUST THE ADVANCE SCOUTS"

DR ROBERT ZUBRIN

The NDX-1 spacesuit, designed by aerospace engineer Pablo de Leon for possible use on Mars, was able to endure the icy temperatures and battering winds during tests in Antarctica

MANNED MISSIONS TO MARS

The leading candidates in the new race to Mars

1. INSPIRATION MARS

With the intention of sending a man and a woman on what has the makings of a historic mission lasting 501 days, Inspiration Mars intends to safely return its crew to Earth after they fly within 160 kilometres (100 miles) of the Red Planet, using technologies derived from NASA and the International Space Station. The plan is to use the gravitational influence of Mars to slingshot their manned vehicle onto a return course back to Earth. They will not land on Mars. The ship's inflatable habitat module will be deployed after launch and detached prior to re-entry into our planet's atmosphere.

2. SPACEX

SpaceX is the world's first privately held company to send cargo to the International Space Station and now the company's founder and CEO Elon Musk intends to send a mission to Mars. First will be a sample-return mission called Red Dragon, that will also look for signs of life. Its long-term plans, however, are to send a manned mission to Mars in a modified version of its already built Dragon capsule. The intention is for the capsule to descend through the Martian atmosphere and land on the rocky surface without the need for a parachute. The capsule's own drag may slow it down enough to allow retro-propulsion thrusters for a controlled enough descent. Eventually SpaceX wants to shuttle 80,000 people to Mars with the intention of colonising the planet.

3. NASA

The National Aeronautics and Space Administration, NASA, is the world leader in Mars exploration. Its most recent development to send humans to Mars in a 2030 timeframe is also currently under review. One possibility is the Orion Multi-Purpose Crew Vehicle that was announced by NASA in 2011. It is hoped that the Orion capsule will be able to carry between two and six astronauts sometime after 2020. It is intended that the 8,900-kilogram (19,600-pound) module will be able to return to Martian orbit using methane propellant made from Mars' soil. Image 3 shows the recent Orion drop test where scientists used a mock-up of the Orion crew module to simulate various water-landing scenarios to account for the different velocities, parachute deployments, entry angles, wave heights and wind conditions on Mars.

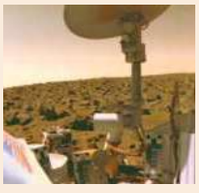
4. MARS ONE

Adamant that the technologies to land the first humans on Mars exist, Dutch start-up Mars One aims to spend an estimated $6 billion to initially send four individuals to the Red Planet. They will be tasked with setting up a habitable outpost based on ready-made hardware that will be sent to the planet in advance. After installing their habitat, the members of the first colony outside of Earth will be expected to grow their own food, mine their own water and oxygen, perform research and, of course, explore a whole new planet.

"SPACEX'S LONG-TERM GOAL IS TO COLONISE THE RED PLANET"

HISTORY OF MARS EXPLORATION

1971
Mars 3
This was the first spacecraft to achieve a soft landing on the surface of Mars but a great dust storm caused a communications failure.



1976
Viking 1 & 2
The Viking programme returned hi-res images, studied the surface and atmosphere and attempted to search for life on Mars.

1997
Sojourner
Sojourner was the first rover to touch down on Mars. It analysed the atmosphere, climate and make-up of the planet's rocks and soil.

DESTINATION MARS

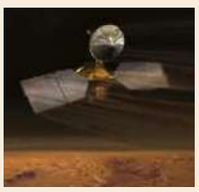
01

02

03

04

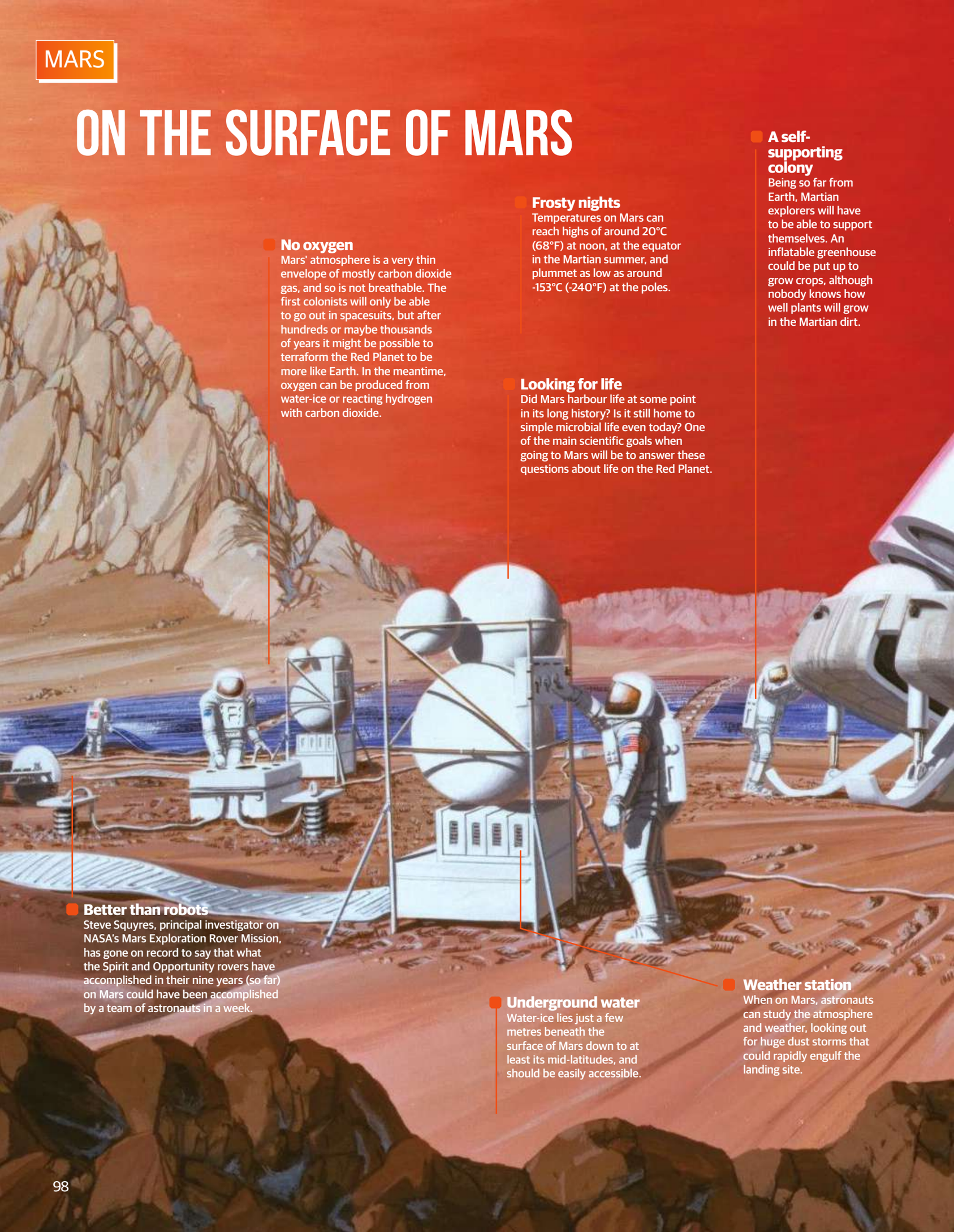
2004
Opportunity
The Opportunity rover has found Martian meteorites, looked into geological processes and studied surface composition.



2006
Mars Reconnaissance Orbiter (MRO)
With a suite of instruments, the MRO continues to analyse Mars' weather and surface conditions.

2012
Curiosity
Curiosity is providing information on the past and present habitability of Mars, as well as taking hi-res images of the landscape.

ON THE SURFACE OF MARS



No oxygen
Mars' atmosphere is a very thin envelope of mostly carbon dioxide gas, and so is not breathable. The first colonists will only be able to go out in spacesuits, but after hundreds or maybe thousands of years it might be possible to terraform the Red Planet to be more like Earth. In the meantime, oxygen can be produced from water-ice or reacting hydrogen with carbon dioxide.

Frosty nights
Temperatures on Mars can reach highs of around 20°C (68°F) at noon, at the equator in the Martian summer, and plummet as low as around -153°C (-240°F) at the poles.

A self-supporting colony
Being so far from Earth, Martian explorers will have to be able to support themselves. An inflatable greenhouse could be put up to grow crops, although nobody knows how well plants will grow in the Martian dirt.

Looking for life
Did Mars harbour life at some point in its long history? Is it still home to simple microbial life even today? One of the main scientific goals when going to Mars will be to answer these questions about life on the Red Planet.

Better than robots
Steve Squyres, principal investigator on NASA's Mars Exploration Rover Mission, has gone on record to say that what the Spirit and Opportunity rovers have accomplished in their nine years (so far) on Mars could have been accomplished by a team of astronauts in a week.

Underground water
Water-ice lies just a few metres beneath the surface of Mars down to at least its mid-latitudes, and should be easily accessible.

Weather station
When on Mars, astronauts can study the atmosphere and weather, looking out for huge dust storms that could rapidly engulf the landing site.

Longer days
The length of a Martian solar day, or sol, is 24 hours and 39 minutes. Astronauts will need special Mars watches that factor in this extra 39 minutes.

Landing craft
In Robert Zubrin's Mars Direct mission, he proposed sending habitation modules to Mars with each new crew, eventually building up to the first settlement on the Red Planet.

Geology
The rocks and dirt on Mars can tell us lots about the past climate in their local environment. Some of the first Martian astronauts therefore may well be geologists.

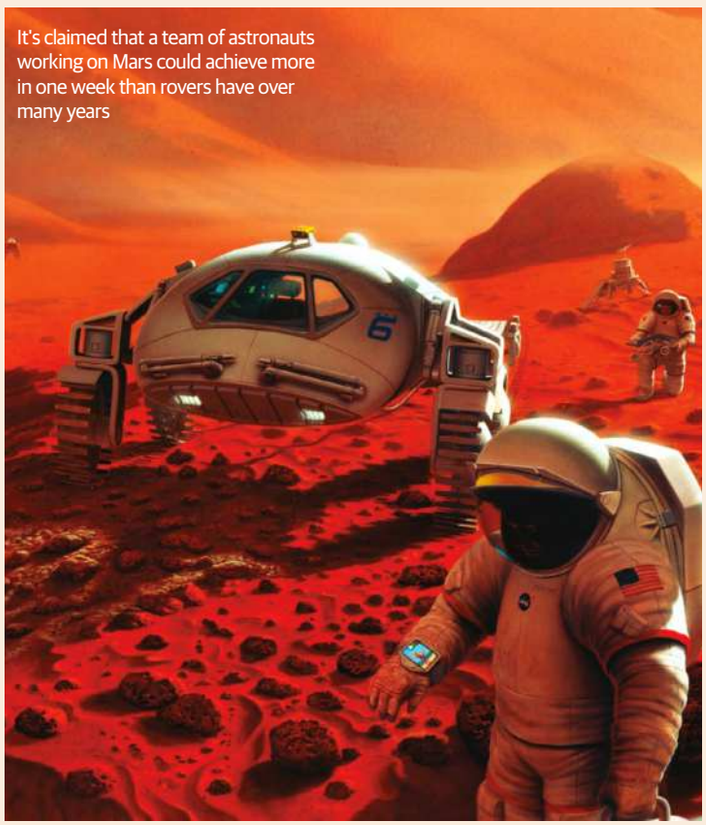
"Really the key question of whether Tito is going to pull this off is whether he can raise the $2 billion needed," said Zubrin at the time. "NASA is funded to a level of $18 billion per year. Now $2 billion is nothing to the government but it is a lot in the private world, but really if NASA had the courage of Tito we would have done this when I proposed it to them in 1995."

Dr Gernot Grömer of the University of Innsbruck and head of the MARS2013 project agreed with Zubrin. "This is a truly ambitious plan," he says. "If you look at their papers where they describe the mission profile, it is well thought through and written by experts who are very good in their subjects. However, for trajectory reasons they [had] to keep the 2018 [or 2021] deadline." That's the big problem, says Grömer. Tito is only funding the first three years of that project until the really high financial demand kicks in. "Developing a transportation system which brings people to Mars and back safely is something that will probably take more than the few years left to the ... deadline," added Grömer at the time of interview. "I honestly wish them all the luck, but I am pessimistic that they can really achieve the super-tight schedule."

Another now-defunct privately funded manned mission was that of Mars One, a not-for-profit organisation based in the Netherlands that intended to establish a permanent human settlement on Mars by 2023, by sending astronauts there on a one-way trip. Remarkably, their plan was to get funding by turning the adventure into a reality TV show. However, Grömer was less convinced by their plans than he is of Inspiration Mars'.

"Unlike the team of Dennis Tito, the Mars One team lacks the expertise and knowledge how to approach such super-ambitious programmes," he says. "Just simply recruiting and maintaining such a large astronaut corps is well beyond their capabilities, not to speak of launchers, habitats,

> "THE BASIC IDEA OF THE MARS DIRECT MISSION IS TO EXPLORE MARS WITH A TRAVEL-LIGHT PHILOSOPHY" DR ROBERT ZUBRIN



It's claimed that a team of astronauts working on Mars could achieve more in one week than rovers have over many years

"THE FIRST HUMAN TO WALK ON MARS IS ALREADY BORN"

Gernot Grömer, MARS2013 project leader

Currently standing as Europe's largest Mars simulation to date, the month-long 'Mars' expedition dubbed MARS2013, which included field tests of two experimental spacesuits, an astronaut injury scenario, tests of autonomous rovers and a cliff-climbing robot, has now been successfully completed – surpassing its very own ambitious objectives. MARS2013 was led by Gernot Grömer. Grömer serves as a board member of the Austrian Space Forum managing a research programme to develop an advanced spacesuit simulator for human Mars expeditions.

What did the MARS2013 expedition entail?

Between 1 and 28 February 2013, the Austrian Space Forum – in partnership with the Ibn Battuta Center in Marrakesh – conducted an integrated Mars analog field simulation in the northern Sahara near Erfoud, Morocco in the framework of the PolAres research programme. Directed by a Mission Support Center in Austria, a small field crew conducted experiments preparing for future human Mars missions mainly in the fields of engineering, planetary surface operations, astrobiology, geophysics/geology, life sciences and others. We had a truly international team from 23 countries, involving more than 100 researchers and volunteers, including the United Kingdom.

What did you learn from the MARS2013 expedition?

We had 17 peer-reviewed research experiments and collected a truly large data set which we are now going to analyse in the next 12 months. We are very much looking forward to a science conference in Vienna in May where we will go into the academic discussion. One of the major outcomes was that we have gained a lot of operational experience in conducting human exploration activities on the surface of another world. This ranges from data on instrument behaviour, biomedical data on the exhaust patterns as well as the efficiency of how to do things such as geoscience in a very efficient manner.

Do you think humans are ready for a trip to Mars?

Yes. It will be the most technically challenging journey our society has ever undertaken, but from the engineering and scientific point of view, we are almost ready. In all our research we haven't encountered a showstopper that told us 'no, you can't go'. This includes hazards such as radiation or human factors but, at the end of the day, I believe we have never been so close to human missions to the Red Planet.

What do you think the future holds for the manned exploration of Mars?

At the Austrian Space Forum we say that the first human to walk on Mars is already born. I personally believe that this generation is the first one to be able to tackle the question of life in the universe on a promising planetary surface for the first time in-situ. If you read a history book in 200 years from now, the economic crisis might only be a marginal chapter, whereas in the long run, our time will be known as the time where we left the planet to discover new worlds.

NASA is preparing for an unmanned test flight of Orion in 2014

"INSPIRATION MARS IS A TRULY AMBITIOUS PLAN. IT IS WELL THOUGHT THROUGH AND WRITTEN BY EXPERTS WHO ARE VERY GOOD IN THEIR SUBJECTS" GERNOT GRÖMER

spacesuits etc. Having big players like SpaceX [behind them] certainly helps, but there is no indication these [partners] are doing it for free. That means, that even large TV companies won't be able to afford such a multi-year programme, not to mention the challenge of keeping the public interest going for such a long time."

In the meantime, as the various companies look to find the funds to reach the Red Planet, full-blown simulated expeditions to Mars are taking place. For example, isolated for 520 days in a mock-up spacecraft in Moscow, five crewmembers got the full brunt of what it would really be like to be making their way to another planet. The Mars-500 project simulated the Earth to Mars shuttle spacecraft journey, the ascent-descent craft and the Martian surface. Delving deep into the psychological and medical effects that long-distance spaceflight would cause, Mars-500 identified possible problems and solutions that cosmonauts were likely to encounter. Subjected to peculiarities such as a lag in communication between 'Mars' and 'Earth', rationing of food and having to live in an enclosed space with others for a long period of time, these Martian

Studying the Martian landscape will provide us with clues as to whether it was once habitable

5 REASONS WE NEED TO GO TO MARS

Why getting mankind to the Red Planet is so important

1 Testing technologies for space exploration

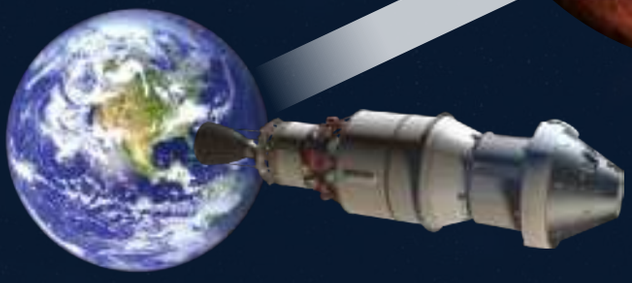
A manned mission to the Red Planet will involve state-of-the art technology but Mars also offers the opportunity to test our new spacecraft and instruments to the extreme. While we have not landed any humans on the Martian soil as of yet, every mission that we have and will continue to send in the future will yield important information from their surroundings. This data will serve as a stepping stone, paving the way for human exploration and the technology that will get us to Mars.

2 Establishing human life elsewhere

At the moment, the only planet that we know of that harbours any complex life is Earth. But what if we humans could exist elsewhere? Mars has the potential, despite its hostile environment, to offer colonisation as an option.

3 Conquering frontiers

Despite being the closest planet to us which bears some similarities to Earth, experts have not let the fact that a manned mission to Mars would be difficult escape their notice. However, for the first time in history, a species on Earth has the knowledge and technology to make the journey to another planet possible. Making the journey to Mars and landing on its surface would, indeed, be a challenge of a lifetime.



4 Looking for life

When asked to envision what life might look like on other planets, it is easy to imagine humans or even sub-human beings roaming their world. Another misconception is that for a planet to be habitable it must have exactly the same characteristics as our Earth. A frozen planet harbouring something as small as a single organism surviving comfortably under an icy planetary crust means that world is habitable no matter the differences in comparison to our home. Mars is similar, while it is unable to support humans without the aid of spacesuits and technology, it can provide clues on the conditions for life both under its surface and on other planets in the Solar System and beyond.

5 Understanding Mars' past and present to look into the future

Clearly expanding our knowledge about Mars is very important, especially if we hope to set foot on the Red Planet sometime in the future. Learning from past and current missions has broadened our horizons immeasurably giving us the confidence to start thinking about what to expect when the first crew touches down on the ruddy soil. Important information that we have discovered is that Mars may have supported life in its past - according to the damp soil that Curiosity found recently. Of course, rovers are not as dextrous as humans which means that they have several limitations when it comes to looking for clues. This is another reason why we need to go to Mars.

ROAD MAP TO MARS

Author of Mars: A Cosmic Stepping Stone, Kevin Nolan speculates on how he thinks Mars exploration will develop in the next seven decades

First manned fly-by 2020-2029

"A European Union-driven sample return mission by around 2025. Human astronaut programme for Mars will be ramped up by the European Union, the United States of America and potentially China. A manned flyby of Mars will occur before 2030 and will be initiated by Dennis Tito but in co-operation with NASA. By contrast, the Netherlands-driven Mars One project for a one-way mission to Mars is notional, impractical and bears no basis on reality."

2010 2020 2030 2040

New Rovers and Landers 2010-2019

"Missions will include NASA's Mars Atmosphere and Volatile EvolutioN (MAVEN), a planned space exploration mission to send a space probe to orbit Mars, as well as ESA's ExoMars, a new Mars Science Laboratory-type rover. Additionally, plans will be firmed up for an international sample return mission. In reality, Dennis Tito's Inspiration Mars, if it is to actually happen, could not happen before 2025."

Deimos mission 2030-2039

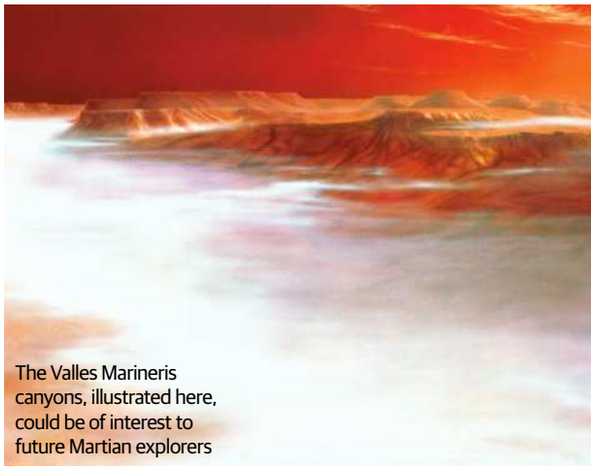
"If we stay on course, we could see a human mission to Mars' furthest moon Deimos and serious Chinese human activity at Mars by either flyby or landing on Deimos."

explorers were tested to their limits. While several crewmembers experienced problems sleeping, avoided exercise to counteract the effects of space travel and would hide away from their crewmates, Mars-500, which ran between 2007 and 2011 and admitted three separate crews, proved a success, with most volunteers reportedly being in good physical and psychological condition.

However, with simulated missions to the Red Planet far from over, experts want to put potential astronauts through even more thorough tests and training. How would they deal with completing actual scientific experiments and walking for miles across the tough Martian terrain?

For such an occasion there was the aforementioned MARS2013 project, which

"THE MARS ONE TEAM LACKS THE EXPERTISE AND KNOWLEDGE HOW TO APPROACH SUCH SUPER AMBITIOUS PROGRAMMES" DR GERNOT GRÖMER



The Valles Marineris canyons, illustrated here, could be of interest to future Martian explorers

500 day stay 2040-2059

"If we're to set people on the surface of Mars then it most likely cannot happen before 2040 (with current forecasts). The notion of placing people on the surface (for a required 500-day stay there) would need significant resources, such as supply missions two years in advance, landing mining nuclear power stations on the surface, return fuel in-situ manufacturing facility. All of these are decades away, so a 20-year interval time period is most likely for actual human missions to land on the surface of Mars."

2050 2060 2070 2080

Long term presence 2060-2079

"When you consider we've been in space for over 50 years and what we've done in that time, one can sense the lengths of time needed, the commitment by countries and governments and the readiness of people. These issues, coupled with the extraordinary technology and budgets required, pushes a long-term human presence on Mars well into the second half of this century in my opinion. An en masse migration of people to the surface of Mars will be another entire agenda well into the next century. Of course, these are speculations, and one multibillionaire could propel all of this forward by decades!"

took place in February 2013. The month-long simulation was initially based at Camp Weyprecht in the Mars-like Moroccan desert, before a three-day excursion collecting rock samples on the way to a second 'landing site' called Station Payer that had been established by four of the ten-member team of analog astronauts. Led by Gernot Grömer, MARS2013 was the biggest Mars simulation ever performed by a European organisation, involving 23 nations and more than 100 scientists. The team performed 17 scientific experiments, as well as field-testing new spacesuit designs and deployable shelters, acting out an astronaut-injury situation and testing cliff-climbing robots. Like Mars-500, a 20-minute 'time delay' was included in all communications with 'Earth', simulating the wait as radio waves travel at the speed of light from Mars to Earth and then back again. Data collected from such simulations is important in planning and preparing for the real thing.

And when is that 'real thing' likely to occur? The Mars enthusiasts at Inspiration Mars, Mars One, the Mars Society and SpaceX would argue that it could happen by the end of the current decade, or the beginning of next. Others, however, are playing it safer, and suggesting beyond 2030 as the most likely date for mankind to reach the Red Planet. In the end it will be decided by who can raise the necessary money and have the courage that Zubrin says is essential to make history by being the first to send people to Mars.

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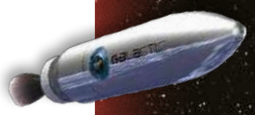
ELON MUSK AND RICHARD BRANSON REVEAL

THEIR FIGHT

MA



IT'S THE BATTLE OF THE BILLIONAIRES: TWO OF THE PRIVATE SPACE INDUSTRY'S MOST EXCITING COMPANIES – SPACEX AND VIRGIN GALACTIC – GO HEAD-TO-HEAD, AND THEY'RE PROVING TO BE FIERCELY COMPETITIVE

FOR

© NASA; ESA; Virgin Plc Ltd; SpaceX; Adrian Mann

There are many similarities between Elon Musk and Richard Branson. For a start, both are serial entrepreneurs: Branson runs the British multinational Virgin Group which has interests in health, entertainment, publishing, travel and motorsport, while Musk is the co-founder of PayPal, the chairman of SolarCity and the chief executive of Tesla.

As a consequence, they are both billionaires, and very well-respected ones at that. Musk may only bein his fifties but, as a brilliant engineer with one of the greatest minds of a generation, he is often favourably compared to the equally genius (yet fictitious) Tony Stark of *Iron Man* fame. Branson is, in his seventies, 21 years Musk's senior, yet he has proven to be an equally worthy real-life superhero in his endeavours. His penchant for balloon travel has seen him get into a few scrapes, but his frequent world-record attempts have seen him become the first man to fly over Mount Everest. Like Musk, however, Branson's current venture is set to take him even further still.

Having delivered cargo to the ISS, the booster lands successfully on the drone ship, Of Course I Still Love You

Branson and Musk are obsessed with space, and they are putting sizeable wedges of cash towards their respective ventures and ambitions. Branson has set up Virgin Galactic with the aim of encouraging passengers to stump up $250,000 for the undoubted pleasure of coasting towards the edge of space in its VSS Unity spacecraft. Musk founded SpaceX, which ultimately plans to populate the Red Planet, allowing anyone who can muster $200,000 the opportunity to embark on the potential one-way trip of a lifetime.

Yet it is here where the two men differ, and where their personal space race assumes a separate path – Musk's sights are set on the Red Planet, while Branson wants it all. "Elon is absolutely fixated on going to Mars, and I think it's his life mission," Branson says. "I am more interested in how we can use space to benefit the Earth, because the Earth is, in my opinion, extremely beautiful, and needs to be protected."

Like Musk, Branson has expressed interest in colonising the surface of the Red Planet – but he's willing to share with the CEO of SpaceX. "Mars is a big place. When we colonise Mars, Musk can have the west end, and we're gonna have the east end," he laughs. "There's room for us both." Speaking on resources for future settlers on Mars, Branson states: "I think there's plenty of frozen water, and those things, so we'll share the water."

Musk, for his part, has indeed long argued that we must colonise the Red Planet. Should we seek to stay on Earth forever, he believes, "there will be some eventual extinction event." A case of do or die, then.

Of course, the end of our own planet is unlikely to happen any time soon, which is perhaps why Virgin Galactic is, for the time being at least, more concerned with letting would-be passengers have a bit of fun (as opposed to SpaceX's aim of saving the human race). Branson's company – which was founded in 2004 – sent its first astronauts into what's officially outer space in 2018, and hopes that tourists will be rocketing skywards soon after, realising a dream which has so far been reserved of those hand-picked for their skills by the world's space agencies.

Should Branson's estimates come true, then it means the 700 or so people signed up for the ride so far (reportedly including the actors Tom Hanks and Angelina Jolie) will enjoy unbuckling and experiencing several minutes of weightlessness in space sooner rather than later. They will be able to see Earth from a far greater height than any aeroplane could take them and, given that space has only been explored by 560 or so people so far, it would be something of a breakthrough. As Virgin Galactic points out on its website, it is opening space to the rest of us (providing we have enough money). Musk is

"ELON IS ABSOLUTELY FIXATED ON GOING TO MARS, AND I THINK IT'S HIS LIFE MISSION" RICHARD BRANSON

"FAILURE IS AN OPTION HERE. IF THINGS ARE NOT FAILING, YOU ARE NOT INNOVATING ENOUGH"

© Gregg DeGuire / Getty Images

ELON MUSK VS

As two of the most successful entrepreneurs

ELON MUSK
Net Worth: $20.2 Billion

1983 Early talent
Having taken an interest in computer programming in his earlier years, at the age of 12, Musk used his new-found skills to create a game called *Blastar*, which he sold to a magazine for $500.

1992-1995 Graduated from university
Musk began his studies at Queen's University in Kingston, Ontario, Canada where he spent two years before moving to the University of Pennsylvania. He has two degrees: one in physics and one in economics.

1995-2002 Headed up PayPal
After founding Zip2, which licensed city guide software to newspapers, Musk set up the online banking company X.com. Following a merger it became PayPal, and Musk emerged as CEO.

2002-Present Founded SpaceX
Musk founded Space Exploration Technologies in a bid to slash the costs of launching spacecraft. Known as SpaceX, it works with NASA and aims to make travel to Mars affordable.

2004-Present Involvement with Tesla Motors
Having invested heavily in Tesla, Musk became chairman of the board. Today he is CEO and Product Architect, presiding over what promises to be an electric car revolution.

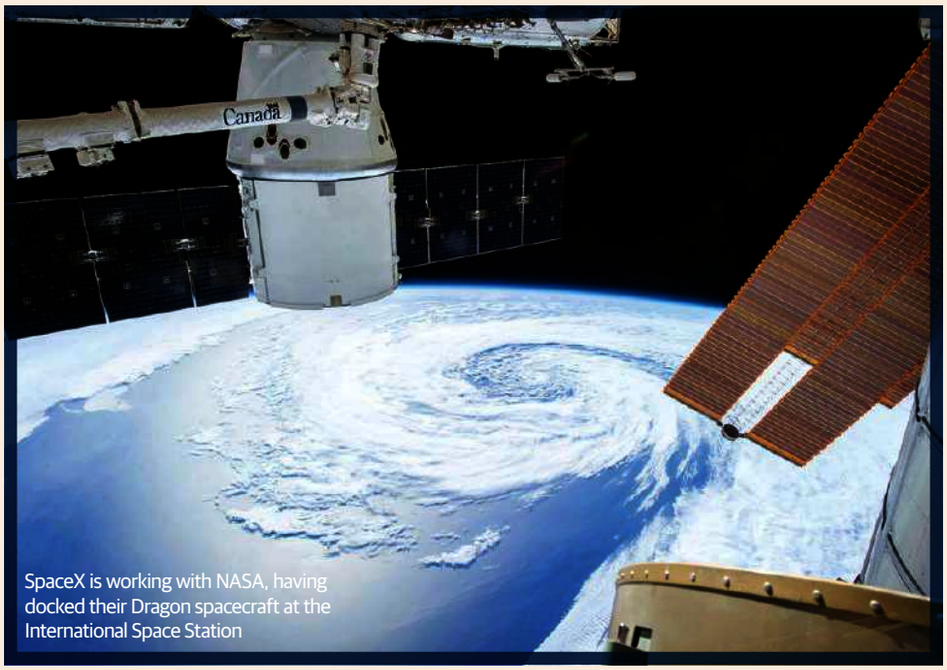
2016-Present Creates The Boring Company
Believing congestion is best relieved by sending traffic underground, The Boring Company's inexpensive tunnels tie in with Musk's concept of a hyperloop – transporting passengers in pressurised capsules in tubes.

looking to do the same but on different terms: with Virgin you get to come back; with SpaceX, the journey to Mars is likely to be one way.

Professor Stephen Hawking was certainly excited about these developments. Branson offered the physicist a place aboard the Virgin Galactic spaceship, giving him the chance to fulfill his "ultimate ambition" of flying. Hawking, who chose the name Unity and whose eye was used as the model for the logo on the side of spacecraft, accepted the offer. "Since that day, I have never changed my mind," he said. Sadly he died before he could take it up. Hawking, who shared the same views as Musk, claimed that we must look at colonising a new planet in the next 100 years, or suffer fatal future consequences. That was music to Musk's ears as he sought a band of space-faring pioneers to make the human race multi-planetary. "However, we will not establish self-sustaining colonies in space for at least the next hundred years, so we have to be very careful in this period," warned Hawking.

Musk wants to ferry people in a pressurised section of what he used to call the Mars Colonial Transporter but is now referred to as the Big Falcon Rocket, or BFR for short. Eventually, he hopes the journey time to the Red Planet will be just 30 days, but the idea is that the spacecraft would carry tons of cargo and building material and enable the colonisers to produce the necessary infrastructure and home comforts. "We'll have 450 tons of luggage and all of the unpressurised cargo to build everything from iron foundries, pizza joints, you name it," he says.

Keen on conquering space, Branson hasn't let returning to the lunar surface escape his notice.



SpaceX is working with NASA, having docked their Dragon spacecraft at the International Space Station


Virgin Galactic's Spaceport America in New Mexico is the world's first purpose-built commercial spaceport


VSS Unity, built by The Spaceship Company, made its first free flight in December 2016, piloted by Mark Stucky and Dave Mackay

© SpaceX; Virgin Group Ltd

RICHARD BRANSON

in the world, they have the impressive CVs to match

RICHARD BRANSON
Net Worth: $5.1 Billion

1966 Set up a magazine
Although Branson struggled with school and dropped out at 16, his entrepreneurial flair was evident early on. In 1968, he launched *Student* magazine making money by selling advertisements.

1970-Present Created Virgin
After selling music by mail order, Branson opened his first record shop on Oxford Street in London, calling it Virgin because he was a beginner at business. A record label followed.

1984-Present Launched Virgin Atlantic
Branson became a thorn in British Airways' side when he launched a rival airline, Virgin Atlantic, quickly establishing itself by the decade's end.

1986 Smashed a world record
Branson crossed the Atlantic in a powerboat for more than three days, but completed the journey two hours faster than the previous record-holder. He has made many other record attempts since.

1993 Received an honorary degree
Having recognised his growing accomplishments, Loughborough University made him an honorary Doctor of Technology. In 2000, he was knighted by Charles, Prince of Wales for his 'services to entrepreneurship.'

2004-Present Launched Virgin Galactic
Not content with launching Virgin Trains in 1997, Branson went a step further and created Virgin Galactic, which aims to open up space travel to anyone able to stump up the cash.


"YOU DON'T LEARN TO WALK BY FOLLOWING RULES. YOU LEARN BY DOING AND BY FALLING OVER"

© Ray Tamarra / Getty Images

The Dragon is a reusable spacecraft developed by SpaceX. It's launched by the Falcon 9 rocket

"Why not have a hotel in space?" he asks. "How fantastic would it be to go and spend a week in a space hotel?"

With the two billionaires keeping their eyes locked on space, we asked Musk whether he was thinking bigger than Branson. "He did name his firm Virgin Galactic. That's pretty big," Musk replied. "It's a bit like your name is Giant and you're actually quite small." He then added: "Technology is not really his whack you know."

Branson counteracted this claim and said he hoped to prove Musk wrong. He added that his own strength was surrounding himself with brilliant people (and indeed, in 2010, Virgin Galactic secured the services of George Whitesides, NASA's former chief of staff, as its chief executive). He also claimed his technology would eventually be able to transport passengers across the Earth in spaceships, and put thousands of small satellites into space: two of the ways Branson says his company's missions will benefit

VIRGIN ORBIT VS SPACEX

Branson and Musk also want to send private satellites into space on behalf of companies and governments

- Virgin Galactic began working on the LauncherOne concept in 2007.
- LauncherOne has a target price of $10 million per flight.
- It can carry up to 300 kilograms (661 pounds) into Sun-synchronous orbits.
- It can also carry up to 500kg (1,100lbs) into a low-Earth orbit.
- After 16 months of modification work, 747-400 was complete.

1 Launching from the ground
SpaceX's launches take place straight from the ground, so here we see the Falcon 9 medium-lift launch vehicle – the world's first partially useable launch system – being prepared for take-off.

1 Mounting the rocket
Virgin Orbit intends to piggyback rockets on Boeing jets; this allows better payload capacity and more flexibility than conventional roacket launches. The LauncherOne rocket is mounted beneath the left wing.

2 Beginning its ascent
As the rocket ascends into space, the two stages are separated. The first stage, which incorporates nine Merlin engines, can begin preparing to come back to Earth.

3 Releasing the rocket
LauncherOne is then released, at which point it fires the NewtonThree – a single main stage engine – for three minutes. It produces about 327 kilonewtons (73,500 pounds) of thrust.

2 Taking off
The Boeing 747-400 – nicknamed Cosmic Girl – takes off with its payload and reaches an altitude of approximately 10,668 metres (35,000 feet).

Virgin Orbit
SpaceX

people intent on remaining on this planet. Perhaps more interesting is the notion discussed on Virgin Galactic's website that "space is not only important for the future of transportation, commerce and science; it's also important for the future of imagination." This is where a line may be drawn between the aims of Virgin Galactic and that of SpaceX in this very modern space race.

Whereas Musk wants to save humankind by physically transporting as many as a million people to Mars on a total of 10,000 trips over the course of 40 and 100 years (the capacity of the spacecraft is 100), Branson wants to do the same by altering mental attitudes. He talks of the Overview Effect, felt by astronauts when they go into space: "Having left the Earth and seen it from thousands of miles away, they gain new perspective on their home planet, and see how tiny the differences are and how great the shared bonds," he writes. "They return with a profound desire to change the world for the better."

Musk appears to think differently. He feels that humans on Earth will only strive to resolve the problems they have created when they realise the mess they're in is real. In that sense, he isn't overly concerned about shaping minds right now, believing it will happen naturally and in due course. "The sustainable energy future, I think, is largely inevitable, but being a space-faring civilisation is definitely not inevitable," he says. Attempting to save humans, wherever they may end up, is more of a priority than purely trying to make Earth alone better, it seems.

Even so, both Musk and Branson are interested in bettering lives through faster transport, which is why they are also locked in a side-battle over hyperloop technology. The brainchild of Musk, hyperloop involves whizzing passengers from A to B on Earth in pressurised capsules. However, while the chief of SpaceX's The Boring Company seeks to build hyperloop tunnels underground, Hyperloop One, in which Branson has invested, prefers tunnels to be overground. Different approaches and different mindsets appear to be at play at every step.

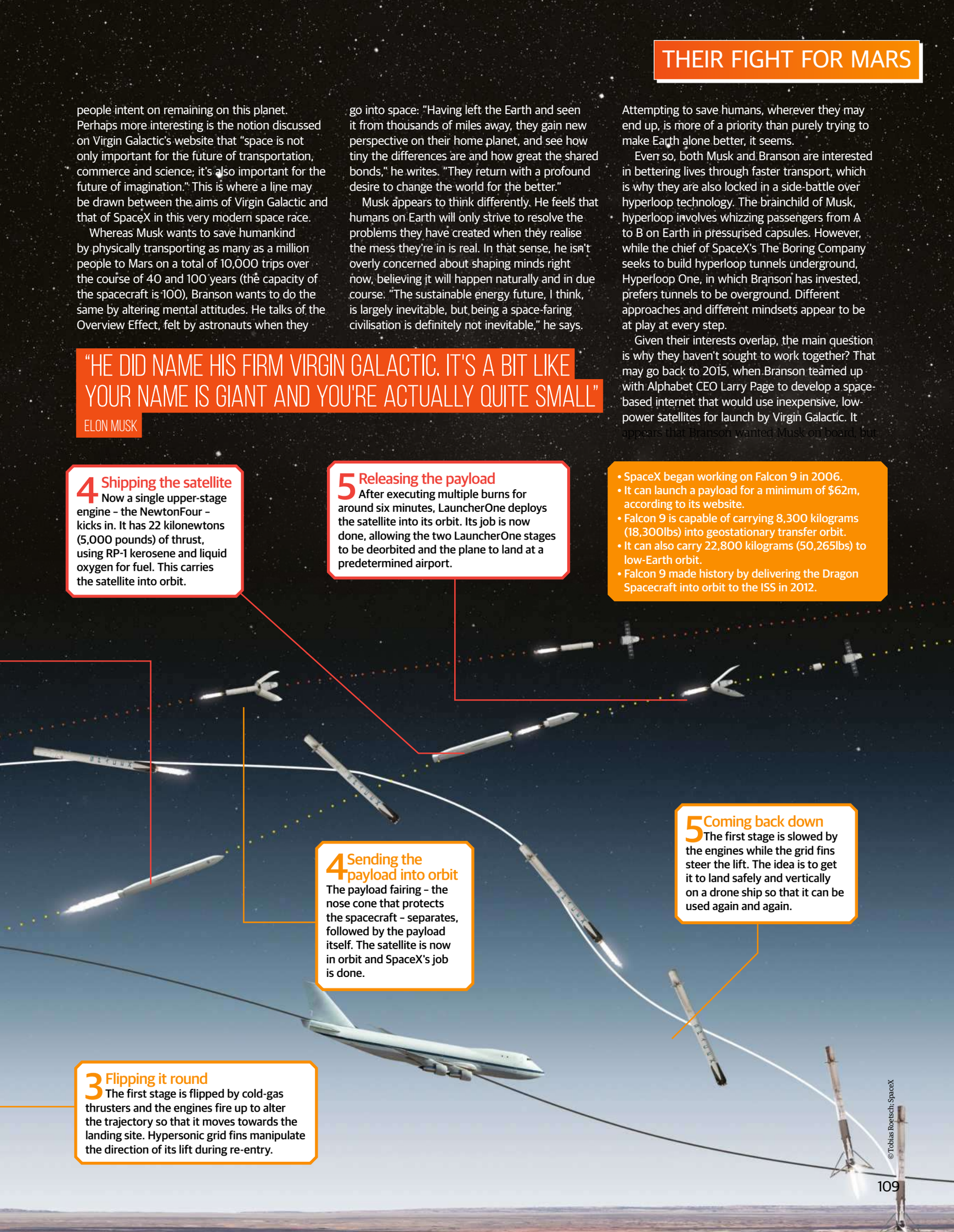
Given their interests overlap, the main question is why they haven't sought to work together? That may go back to 2015, when Branson teamed up with Alphabet CEO Larry Page to develop a space-based internet that would use inexpensive, low-power satellites for launch by Virgin Galactic. It appears that Branson wanted Musk on board, but

> "HE DID NAME HIS FIRM VIRGIN GALACTIC. IT'S A BIT LIKE YOUR NAME IS GIANT AND YOU'RE ACTUALLY QUITE SMALL"
>
> ELON MUSK

4 Shipping the satellite
Now a single upper-stage engine – the NewtonFour – kicks in. It has 22 kilonewtons (5,000 pounds) of thrust, using RP-1 kerosene and liquid oxygen for fuel. This carries the satellite into orbit.

5 Releasing the payload
After executing multiple burns for around six minutes, LauncherOne deploys the satellite into its orbit. Its job is now done, allowing the two LauncherOne stages to be deorbited and the plane to land at a predetermined airport.

- SpaceX began working on Falcon 9 in 2006.
- It can launch a payload for a minimum of $62m, according to its website.
- Falcon 9 is capable of carrying 8,300 kilograms (18,300lbs) into geostationary transfer orbit.
- It can also carry 22,800 kilograms (50,265lbs) to low-Earth orbit.
- Falcon 9 made history by delivering the Dragon Spacecraft into orbit to the ISS in 2012.



4 Sending the payload into orbit
The payload fairing – the nose cone that protects the spacecraft – separates, followed by the payload itself. The satellite is now in orbit and SpaceX's job is done.

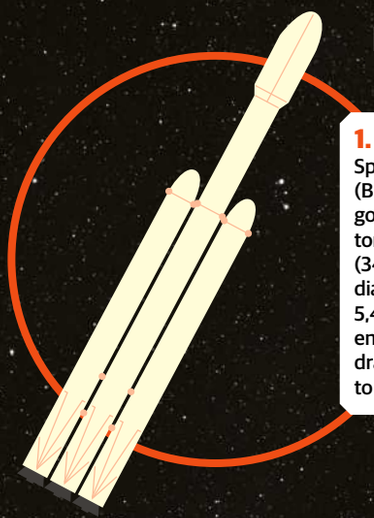
5 Coming back down
The first stage is slowed by the engines while the grid fins steer the lift. The idea is to get it to land safely and vertically on a drone ship so that it can be used again and again.

3 Flipping it round
The first stage is flipped by cold-gas thrusters and the engines fire up to alter the trajectory so that it moves towards the landing site. Hypersonic grid fins manipulate the direction of its lift during re-entry.

© Tobias Roetsch; SpaceX

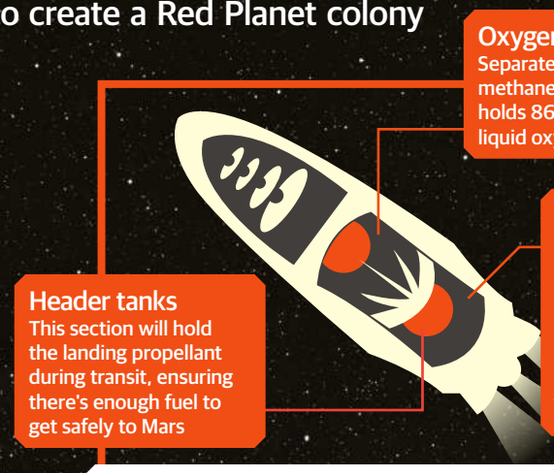
"MARS BELONGS TO ELON"

How Elon Musk is planning to create a Red Planet colony



1. Build a really big rocket

SpaceX is creating the Big Falcon Rocket (BFR) – a rocket larger than any that have gone before. Weighing a total of 4,400 tons at liftoff, and standing at 106 metres (347ft) tall and nine metres (30ft) in diameter, it will have a liftoff thrust of 5,400 tons. It will also have 31 Raptor engines and be fully reusable, helping to dramatically reduce costs. SpaceX hopes to have it ready for use in the early 2020s.



Oxygen tank
Separated from the methane is a tank that holds 860 tons of liquid oxygen

Fuel tank
The fuel tank will hold 240 tons of methane at the bottom of the spacecraft, just above the engines

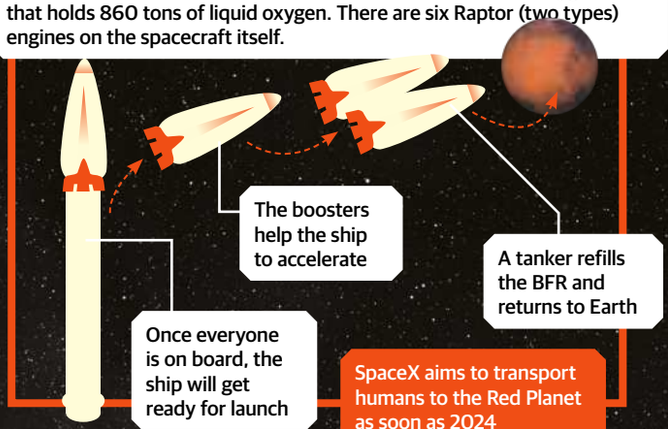
Header tanks
This section will hold the landing propellant during transit, ensuring there's enough fuel to get safely to Mars

2 Create a humongous spaceship

At the tip of the BFR is the payload: the section where passengers will stay and where the cargo will be stored. It will have 40 cabins and large common areas along with a galley and a solar storm shelter, plus lots of entertainment: it's a long journey after all. SpaceX says the cabin will be pressurised to a volume of 825m³, which is greater than that of an A380 aeroplane. It's thought 100 people will complete each journey.

3. Get it into space

The BFR will take off vertically, propelled skywards by its 31 engines. When it gets through the Earth's atmosphere, the booster will detach and power back to Earth. The spaceship will then continue on its way, making use of the fuel tank that holds 240 tons of methane and the oxygen tank that holds 860 tons of liquid oxygen. There are six Raptor (two types) engines on the spacecraft itself.



The boosters help the ship to accelerate

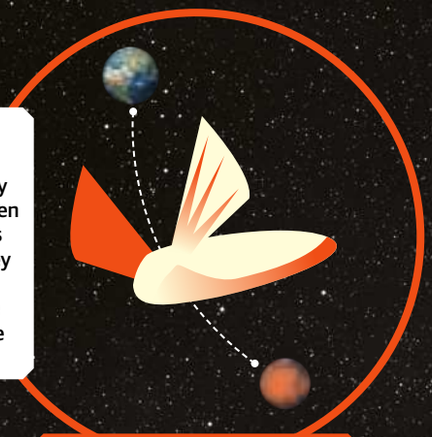
A tanker refills the BFR and returns to Earth

Once everyone is on board, the ship will get ready for launch

SpaceX aims to transport humans to the Red Planet as soon as 2024

4. Make the long journey

Cries of "are we nearly there yet?" are inevitable, because the journey to Mars will take anywhere between three and six months. Solar panels will be deployed during the journey and this will power some of the much-needed entertainment. The views should be spectacular as the Red Planet looms into view.



The BFR will make use of advanced heat-shield technology

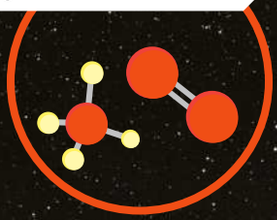
5. Ensure a safe landing

When it gets to Mars, the spaceship's legs will deploy for a vertical landing, but it's fair to say touching down on the surface will be no simple feat. The aim, says Musk, is to make it as safe as landing a commercial plane, so although it will land under the retro-propulsive thrust of two Raptor engines, it could also do it with one if there was an engine failure. Time for the passengers to disembark.

The idea is that the founding Martians will be able to enjoy the spoils of a new galactic city

6. Get it back to Earth

Since the spaceship is reusable and there is potential that some people may want to come back to Earth, the spacecraft needs to take off from Mars and return. The idea is to use the Red Planet's abundant supply of CO_2 and water ice to locally produce CH_4 and O_2 propellant. Once it arrives on Earth, it will be checked over and placed on a BFR again, ready for the next group of Mars-bound passengers.



"was saddened that Elon didn't consider working with Larry and me."

Instead, SpaceX and Virgin Galactic are charting their own separate paths, and they are both proving to be successful. In October 2017, Virgin Galactic was given a boost thanks to $1 billion in funding from Saudi Arabia, authorised by its new Crown Prince Mohammed bin Salman. "This will enable us to develop the next generation of satellite launches and accelerate our programme for point-to-point supersonic space travel," Branson says. This is, in some sense, another sub-race, because SpaceX is also hoping its rockets will enable point-to-point Earth travel too. Musk has suggested future passengers could wing their way from New York to Shanghai in as little as 39 minutes at over 18,000 kilometres-per-hour (11,372 miles-per-hour).

Branson is also looking to go toe-to-toe with SpaceX in bagging commercial and government contracts. He is doing so with a new space-centred company called Vox Space, based in southern California. It's aim, according to its website, is to "provide the national security community of the USA and allied nations with the ability to launch services for small satellites bound for low-Earth orbit". Another spin off, Virgin Orbit, will also launch services for small satellites, but those government contracts are a lucrative business. SpaceX offers rockets capable of carrying 22,680-kilograms (50,000 pounds) to low-Earth orbit, compated to the 181-kilograms (400-pound) capacity of Vox. It is also designing a spacecraft for NASA.

While Virgin Galactic and SpaceX are not competing with each other to be the first to Mars, they are going head-to-head in other areas. So, while, SpaceX isn't planning on launching its first mission to Mars before 2022 (a timescale even Musk readily admits is "aspirational"), their other plans should come to fruition sooner. Branson is set to win the personal space race, however, since he is very much on course to be the first of the pair to journey into space, having flown to its edge in a rocket plane in July 2021.

He is certainly keeping himself fit and active so that he can make the journey, even though he admits that the Virgin Galactic project has been one of his greatest challenges. It has already claimed the life of test pilot Michael Alsbury when the first version of the SpaceShipTwo disintegrated over the Mojave Desert in 2014. Virgin Galactic has since received its operating license from the US Federal Aviation Authority, and Branson is also taking part in centrifuge training, which involves being spun to a high speed in order to simulate the feeling of gravity. His body is prepared for the likely strains that space travel will place on it.

Musk, on the other hand, is far less likely to be on his spacecraft to Mars in the early stages, although he does want to go eventually. "I'd have to have a really good succession plan [for SpaceX], because the likelihood of death is very high," he explains. He is understandably worried about not seeing his children grow up and he frets that investors may decide, in his absence, not to continue with the Mars plan. But he has said that he wants to die on Mars: "I can't think of anything more exciting than going out there among the stars," he smiles.

One thing's for sure, though, these are fascinating times for both Musk and Branson, and it's heartening to see that the pair are so passionate about space and it's exploration. The levels of investment in their respective endeavours truly brings them together, and there's no suggestion that a bit of healthy competition is a bad thing. With so many clever scientists and engineers working on the various projects, and two driven bosses, we will inevitable reach new heights. The future is indeed looking bright.

"I CAN'T THINK OF ANYTHING MORE EXCITING THAN GOING OUT THERE AMONG THE STARS" ELON MUSK

Hyperloop technology was originally an idea coined by Musk, with Branson investing in the American company Hyperloop One in 2017

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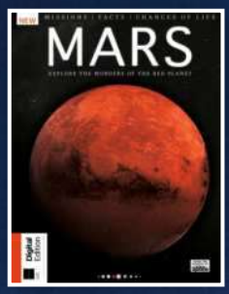

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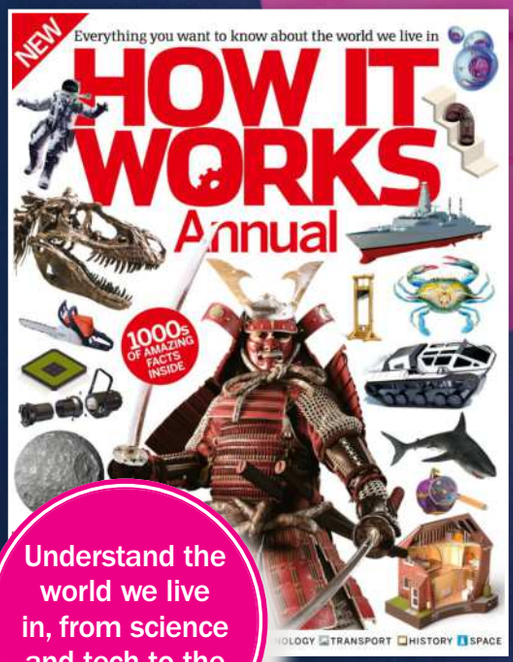

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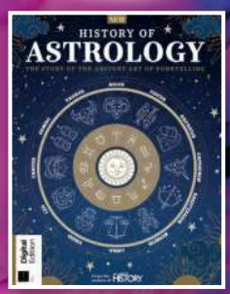

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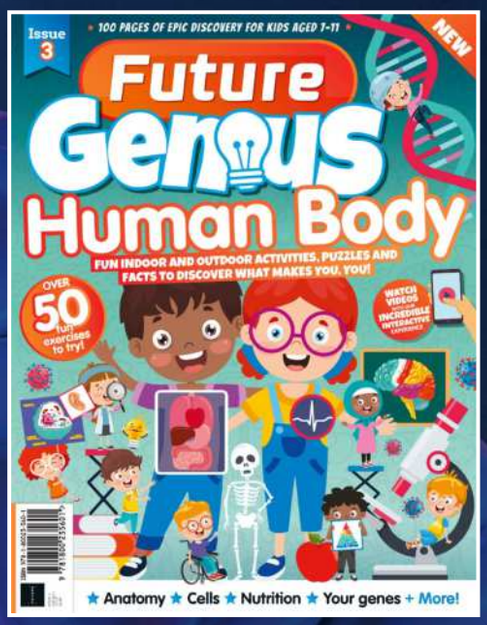

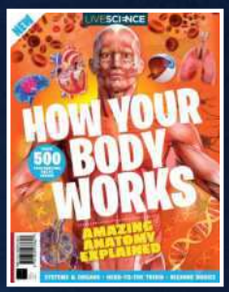

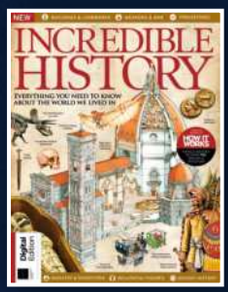

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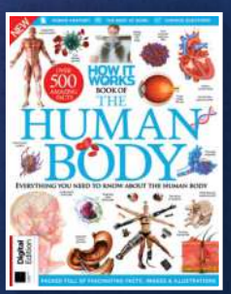

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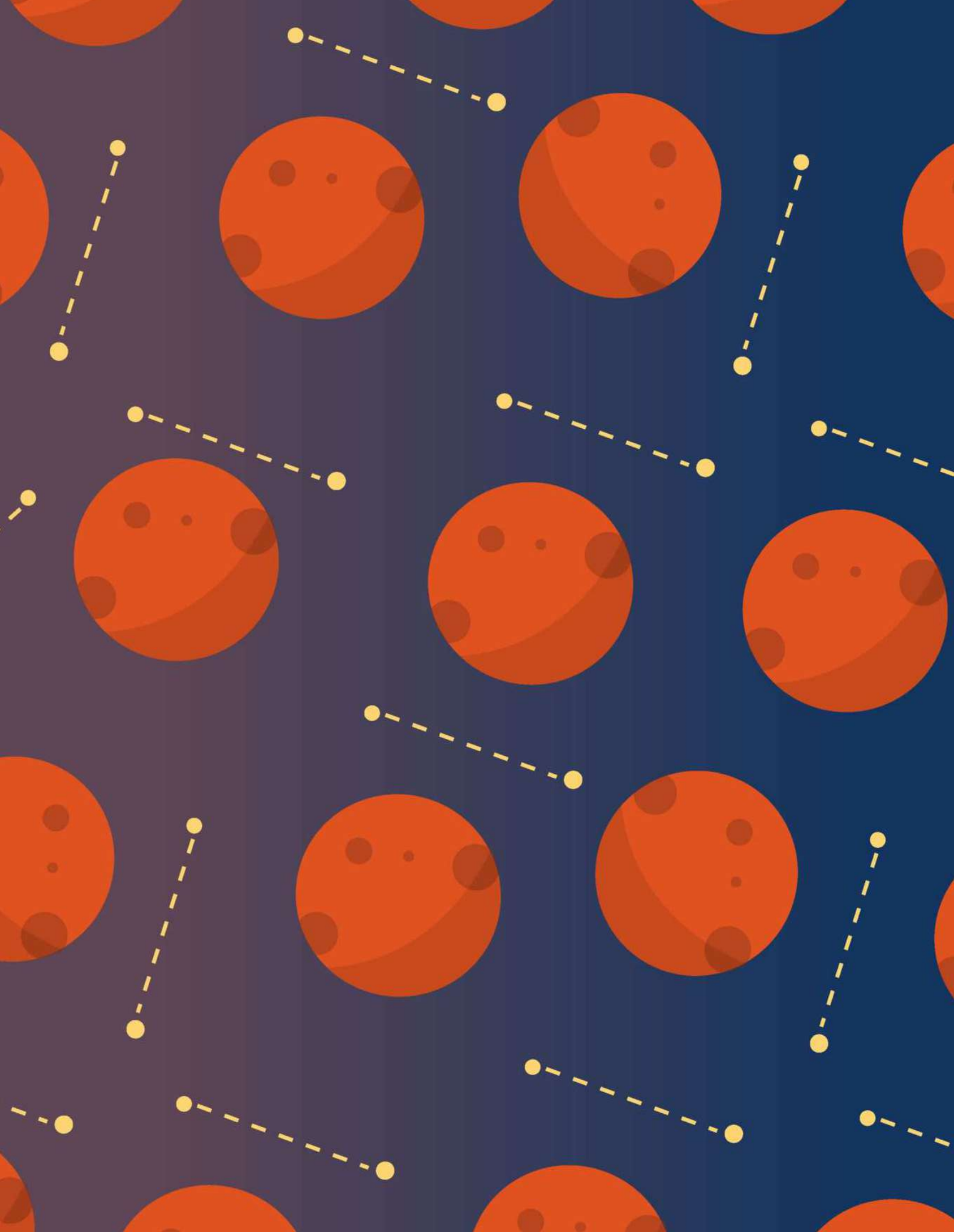

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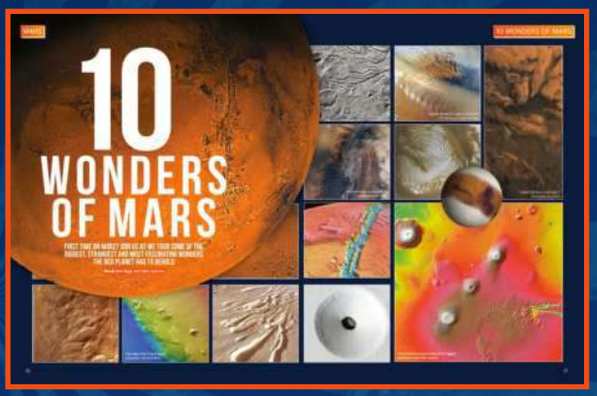

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